CALIFORNIA
ENERGY
COMMISSION

PUBLIC INTEREST ENERGY RESEARCH PROGRAM

Climate Change Research, Development, and Demonstration Plan

CONSULTANT REPORT

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CALIFORNIA ENERGY COMMISSION

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The Public Interest Energy Research (PIER) Program Environmental Area

The Public Interest Energy Research (PIER) program was created following the deregulation of California's electricity service industry (1996 Status, Chapter 854, hereinafter referred to as Assembly Bill (AB) 1890). Article 7 of AB 1890 was enacted to ensure that the benefits obtained from important public purpose programs, such as public interest energy research, development, and demonstration (RD&D), would not be lost in the newly deregulated environment. California's electric investor-owned utilities collect $62 million annually from electricity ratepayers to fund the PIER program. In September 2000, the Legislature passed, and Governor Gray Davis signed into law, Senate Bill (SB) 119 (Sher) and AB 995 (Wright), which extended the PIER Program surcharge to January 2012.

The PIER Program is organized in six PIER Program funding areas:

1. Residential and Non-Residential Buildings End-Use Energy Efficiency
2. Industrial / Agricultural / Water End-Use Energy Efficiency
3. Renewable Energy Technologies
4. Environmentally Preferred Advanced Generation
5. Energy-Related Environmental Research
6. Energy Systems Integration

Each of these areas funds and conducts energy-related research in the public interest, for the benefit of California citizens.

The Public Interest Energy Research Energy-Related Environmental Research area (otherwise called the *PIER Environmental Area*, or *PIEREA*) is responsible for addressing the environmental impacts and beneficial uses of electricity in California. As defined by the PIER strategic plan, the overall mission of the PIEREA is to:

> Develop cost-effective approaches to evaluating and resolving environmental effects of energy production, delivery, and use in California, and explore how new energy applications and products can solve environmental problems.

Executive Summary

Overview

The PIER Program's Role in Climate Change Research

Climate change is no longer a hypothetical or distant possibility—it is occurring, and is likely to have a profound impact on human society and the natural environment over the coming decades. Climate change and its global impacts are the focus of an intense and broad-based international research effort in the natural and social sciences. However, understanding the nature and potential consequences of climate change on regional scales, and specifically in California, is a challenge we have just begun to meet. The California Energy Commission's PIER (Public Interest Energy Research) program has prepared this research plan to support California's intensifying efforts to understand how climate change will affect the state's social, economic, and natural systems; and to help provide policy-makers with the knowledge and tools they need to anticipate and plan for these impacts.

The PIER program was created to ensure that California citizens fully benefit from important public purpose programs involving energy research, development, and demonstration (RD&D). This work is supported by California's electricity ratepayers through an annual $62 million collected by the state's investor-owned electric utilities, and this fund is managed by the Energy Commission.

Within PIER, the Energy-Related Environmental Research area (otherwise called the *PIER Environmental Area*, or *PIEREA*) is responsible for addressing the environmental impacts and beneficial uses of electricity in California. As defined by the PIER strategic plan, the overall mission of the PIEREA is to:

> Develop cost-effective approaches to evaluating and resolving environmental effects of energy production, delivery, and use in California, and explore how new energy applications and products can solve environmental problems.

In the context of this mission, there are three primary reasons for a major PIEREA research effort on climate change. First, electricity generation in (or for import into) California is a major source of greenhouse gas (GHG) emissions. Second, there is a high likelihood that higher temperatures attributable to climate change will increase energy consumption—and particularly electricity consumption—in California. Third, by altering precipitation patterns across the West, climate change is likely to affect the supply and cost of hydropower, which represents about 20% of in-state electricity generation. Thus, it is necessary for PIEREA to study both how to mitigate the climate-related effects of electricity generation and how to maintain reliable and affordable flows of electricity to California's households and businesses in the context of a changing regional climate.

The PIEREA Climate Change RD&D Plan

The PIEREA Climate Change RD&D Plan provides a strategic vision for supporting climate change research in California, focusing on research areas that will be funded over the next five years. This plan is drawn primarily from climate change research roadmaps commissioned by the PIER program. Under the direction of PIEREA staff, the roadmaps were developed by recognized climate change experts. The following roadmaps were produced:

- Modeling Regional Climate Change in California (**Larry Gates**, Lawrence Livermore National Laboratory)
- The Effect of Global Climate Change on California Water Resources (**Maurice Roos**, California Department of Water Resources)
- Ecological Impacts of a Changing Climate (**Rebecca Shaw**, Department of Global Ecology, Carnegie Institution of Washington, Stanford University)
- Carbon Sequestration in California's Terrestrial Ecosystems and Geologic Formations (**Edward Vine**, California Institute of Energy Efficiency and **Mark Wilson,** Consultant)
- Developing Greenhouse Gas Supply Curves for In-State Sources (**Mike Rufo,** Xenergy, Inc.)
- The Economics of Climate Change Mitigation and Adaptation in California (**Alan H. Sanstad,** Lawrence Berkeley National Laboratory)

The roadmaps were developed with generous input from technical representatives of multiple state agencies (i.e., the California departments of Water Resources, Food and Agriculture, Forestry and Fire Protection, and the Air Resources Board); researchers from the University of California, California State University, and other universities; national laboratories; environmental groups; federal agencies; the Electric Power Research Institute; electric utilities; California irrigation districts; the California Climate Registry; and the United States Global Change Research Program.[1]

Collectively, the roadmaps have become a de facto statewide climate change research plan. The research recommended in the roadmaps is, however, beyond the resources available to the PIER program. Therefore, in developing funding recommendations for the Energy Commission, research areas were evaluated on their relevance to the energy sector, their potential to advance the science in a critical area, and the clear need for the state to support research on climate change and California that is not currently being funded by the federal government or other research funding agencies. PIEREA is already funding work to address many of these issues (as are many other public and private entities), and the goal of this effort is to build upon that work and leverage the collective expertise in this area.

[1] The California Energy Commission is publishing the roadmaps as attachments to the PIEREA Climate Change RD&D Plan.

The plan itself is a "living document" that will be revised periodically to address other high-priority needs as they arise or are identified, as will the roadmaps on which the plan was based. In addition, PIEREA will continue its collaborative effort by developing roadmaps that address other issues, such as climate change impacts on human health and on forests and agriculture in California.

An Integrated, Collaborative Research Approach

PIEREA's role in climate change research is one of cooperation and coordination with other state and federal agencies, research programs, and funding agencies. This approach avoids duplication of efforts, leverages limited resources, and ensures the production of high-quality, policy-relevant research for California. PIEREA will fulfill this role by seeking input from different stakeholders throughout the execution of this research plan, and by organizing regular scientific climate change workshops and conferences, where the work funded by PIEREA and others will be presented—with the goal of sharing results and building collaborations. PIEREA has joint projects with the California Departments of Forestry and Fire Protection, Water Resources, and Food and Agriculture. PIER will continue to work with these and other state agencies. Similar work is under way with federal agencies and the U.S. Climate Change Science Program.

Climate Change and California

Global and Regional Climate Change

There is now a broad scientific consensus that the global climate is changing in ways that are likely to have significant socioeconomic consequences, and that these changes will continue and probably intensify through the twenty-first century. Climate change research findings have been detailed by the authoritative International Panel on Climate Change (IPCC). In its Third Assessment Report (TAR), released in 2001, the IPCC concluded that the increase in the global average surface temperature during the twentieth century "…is likely to have been the largest of any century during the past 1,000 years." Moreover, the modeling studies considered by the IPCC project that this temperature will increase by 1.4 to 5.8°C (2.5 to 10.4°F) over the period 1990 to 2100.

There is also mounting evidence that observed global climate change is due substantially to human activities—specifically the emissions of GHGs such as carbon dioxide, methane, and nitrous oxide. The TAR concludes that "there is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities." A recent report prepared by the U.S. National Academy of Science at the request of the Bush Administration confirms this finding.

Both scientific and socioeconomic global climate change research has focused mostly on scenarios of gradual and smooth shifts, primarily as measured by long-run equilibrium increases in mean global surface temperature. Such scenarios do not apply directly to regional scales, however, and understanding and projecting regional climate change is a significant research challenge (as discussed in the Research Agenda section, below). Nevertheless, current scientific understanding indicates that the character of climate change in California may be much more in the nature of abrupt shifts, greater variability, and an increased number of “extreme events” such as droughts and floods than long-run smooth changes in trends. Moreover, human-induced climate change affecting California directly will be superimposed upon, and possibly interact with, existing natural patterns and variation in the regional climate. For these reasons, anticipating California-specific climate change impacts is more a challenge of assessing risks and uncertainties than of making specific predictions. Enough is understood regarding the regional climate to anticipate some possible impacts, and in certain cases, relate them to present day trends. However, improved data and tools need to be developed to better identify and quantify impacts and interactions, and to provide policy-makers with the information they need to formulate robust policies that will mitigate impacts from climate change.

Climate Change Impacts on California

Climate change and variability will have important implications for a number of California’s natural and socioeconomic systems. The state is one of the most diverse regions—ecologically, geographically, and culturally—of any in the world. California’s 1.3 trillion dollar economy is the largest among the U.S. states, and would rank in the G-7 group of the seven largest OECD economies were it an independent country. California is the most populous and fastest-growing state in the nation, and climate change impacts will exacerbate the environmental and economic stresses already occurring from continued development and urbanization. Natural climatic events such as floods, mudslides, coastal erosion, droughts, fires, and heat waves also affect the state’s economy and quality of life. Climate change could further increase the variability and impact of these events, affecting all of the state’s people and places, and the valuable natural and engineered systems on which we depend.

A wide range of potential impacts to California’s critically important engineered systems, natural resource systems, economic and health systems, and ecosystems may be caused by climate change and variability. Impacts to any one of these interrelated systems invariably affects another, and could stem from a variety of causes:

- Changes in precipitation intensity and distribution could reduce water availability for hydroelectricity generation; temperature increases could increase summer peak-load electricity demand; and extreme weather events and fires could threaten or damage transmission and distribution infrastructure.

- California’s economy depends critically on an extensive engineered water infrastructure. In addition to its role in hydroelectric generation, this system provides water to California agriculture as well as to urban households and businesses. Climate change may exacerbate the already critical stresses on this system, affecting both water availability and cost.

- Ecosystems in California, whether natural or managed, will likely be affected by climate change and variability. Plants and animals, already pressured by human encroachment, will be further stressed by temperature changes and shifting precipitation. Wildlife will have to adapt to changing habitats; some species will move, others may alter their behavior, and some may not be able to adapt. The number of threatened and endangered species in the state (already the largest in the contiguous 48 states) could rise significantly from these combined stresses.

- Human health in the California region is likely to be affected by climate change and variability. Most likely, greater climate variability and changes in climate patterns will cause both direct and indirect effects. Direct health impacts will stem from the extreme events mentioned above, which could result in flooding and landslides, prolonged high temperatures, and increased fire frequency and intensity. Secondary or indirect effects include damages to infrastructure—causing, for example, sanitation and water treatment problems leading to an increase in water-borne infections. Air quality impacts, such as increases in ground-level ozone as a result of higher temperatures, may also cause secondary health impacts.

Electricity Generation Serving California is a Major Source of Greenhouse Gas Emissions

In addition to addressing the risks posed by potential climate change impacts, California may in the coming years be compelled to mitigate its contributions of GHGs to the global atmosphere, under policies originating at the international, national, or state levels. Carbon dioxide (CO_2) emissions represent about 85% of the in-state GHG emissions, and the vast majority are generated from the combustion of fossil fuels. In-state electricity generation contributes about 16% of the annual CO_2 emissions (about 55 million tons per year) from all the sources located in the state. California's electricity consumption, however, is responsible for much higher emissions, because the state imports about 30% of the electricity consumed in the state from other states—some of it from coal-burning power plants. Burning coal generates about twice the amount of CO_2 per unit of energy released during combustion than natural gas, the fuel of choice in California. As a result, out-of-state power plants emit more CO_2 than in-state power plants. If emissions from out-of-state power plants serving California were counted as in-state emissions, power plants would contribute about 28% of the total CO_2 emissions in the state's inventory.

PIEREA Research Agenda and Benefits

Overview

The development process for PIEREA's climate change research program identified a range of interrelated research needs in the areas of climate change monitoring, analysis and modeling; estimating costs of reducing GHG emissions; impacts of climate change on California's water and ecological resources, sequestration of carbon in the state's terrestrial ecosystems and geological formations; and the economics of climate change mitigation and adaptation in the state. The research agenda summarized in the following sections was developed by evaluating the detailed research needs discussed in the PIER roadmaps and selecting projects for the first five years of funding, according to the criteria outlined in the first section of this Summary. This research plan is intended to provide a strategic California climate change program that can be enhanced with collaboration and funding from other state, federal, and private entities. Two of the research areas described in the following sections play distinctive roles in the plan: climate change monitoring, analysis, and modeling would provide critical inputs to all other areas, while the research on the economics of mitigation and adaptation would integrate the results of the other areas and help depict their potential policy implications.

Climate Change Monitoring, Analysis, and Modeling

Impact and mitigation analyses play an important role in enabling California planners and policy makers to craft effective plans and regulations. These analyses rely to a large extent on the results of sound climate change monitoring, analysis, and modeling; therefore, the development of climate change scenarios for California, using the best scientific tools, must be a priority for California and PIEREA.

General circulation models (GCMs) are complex computer models that are used to simulate natural and human-induced climate changes on a global scale. They make use of large grid cells (on the order of 300 km) that cannot resolve important topographic features such as the Sierra Nevada and the coastal mountain ranges, as shown in Figure 1. The resolution of most GCMs offers no detail of California's topography. At the 50-km resolution, common to many regional models, the Central Valley and Sierra Nevada begin to be discernible; whereas, a grid size of 10 km reveals their regional structures, as well as those of the coast ranges. Scientists working on impact and adaptation analyses need climatic data at a much higher geographical and temporal resolution than that available from GCMs.

PIEREA-sponsored research on regional climate would address the following questions:

- How is the climate in California changing in relation to the historical and pre-historical conditions? How much of this change can be attributed to natural variability?
- What are the expected signals of a changing climate in the state, and how they should be monitored?
- What are the potential changes of California climatic conditions, based on the increased concentration of GHGs in the atmosphere?
- What is the estimated likelihood of the different climatic scenarios?
- How would the frequency and severity of extreme events change in the future?

- What is the potential from abrupt climate changes in the state, and how would the new potential climate look?
- Which GCMs are most appropriate for providing inputs to the study of regional climate change affecting California?

PIEREA is recommending the following research to address those questions:

Compilation and Analysis of Historical Climate and Measurement of Key Variables

PIER, in conjunction with other state agencies, would sponsor and contribute to the development of a comprehensive California-focused climate database, using existing data sources and adding key measurement sites as needed. Existing data would be quality-checked and digitized, if necessary. The database would be used to understand how climate has changed and is changing in the state, and for evaluation of regional models. Researchers would conduct additional meteorological and hydrological monitoring and measurements, especially for high-elevation areas where changes in

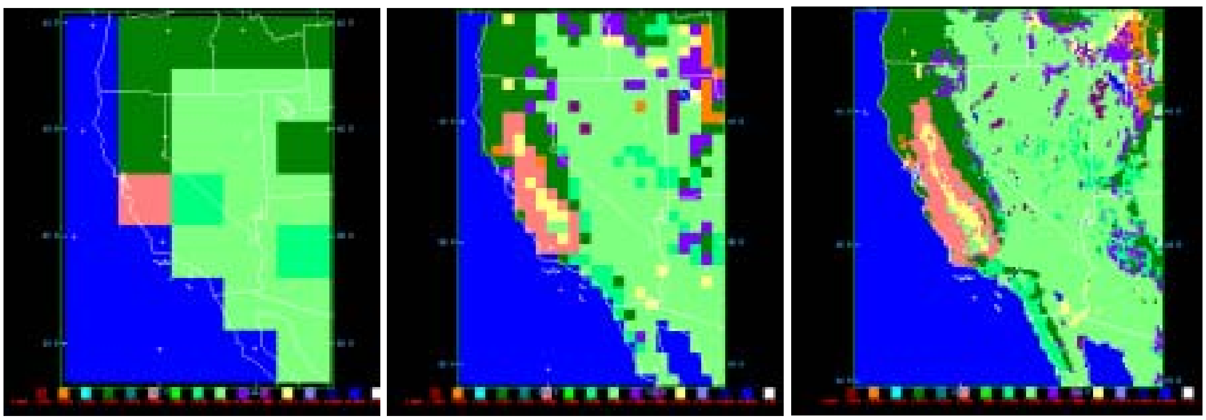

Figure1. Resolution at GCM scale, 50 km, and 10 km.

snowmelt are a concern. PIEREA would support the development of non-intrusive and less expensive remote monitoring systems to increase substantially the number of monitoring sites and monitoring parameters measured in key regions of the state. **Benefits:** This effort would facilitate better snow-level forecasting and detection of subtle climatic changes, help develop improved models based on higher-quality and more comprehensive data, enhance the state's ability to determine to what extent the observed increase (or decrease) in cooling degree-days (or heating degree-days)[2] is attributable to increased urbanization, and improve understanding of energy consumption patterns and climate.

Intercomparison of Regional Climate Models

PIEREA, in conjunction with other state agencies, would fund the development of a modeling protocol to validate and intercompare regional climate models (RCMs), which includes numerical and statistical models and other promising modeling approaches. Once developed, PIEREA would

[2] Increased cooling or heating degree-days represent an increase in the amount of energy needed for cooling or heating houses and buildings.

compare models against each other and against observational data, at resolutions needed for climate change applications, to identify characteristic model errors. When researchers identified the most effective model(s), they would identify a common nested model domain[3] and develop a regional modeling protocol. Further research would compare statistical methods against numerical RCMs and historical data not used in the development of the statistical methods. **Benefits:** Standardization of modeling protocols would enable the state to evaluate models and compare data, and identify the most appropriate RCM(s) for California applications.

Development of Climate Scenarios for California

The best-performing RCMs from the previous project would be used to develop ensembles of regional climate change projections, which would allow researchers to assign probability to the different climate scenarios. This work would be coordinated with the projects on impact and adaptation analyses, to ensure that the climate modeling results provide adequate geographical and temporal resolutions for the parameters needed. **Benefits:** California would gain the ability to develop a comprehensive understanding of likely regional climate changes that will affect its hydrology, agriculture, and natural ecosystems.

Impacts of Climate Change on California Water Resources

California's water resources contribute to the success of every public and private sector activity in the state. In the electricity sector, hydroelectric generation represents about 20% of the electricity generated in the state, and California imports a significant amount of hydropower from the Pacific Northwest.

PIEREA-sponsored research on regional climate would address the following questions:

- How may climate change and population growth affect California's future water resources, including hydropower production and ecological systems?
- How should the operation of hydropower facilities be improved to be able to cope or benefit, if feasible, under expected significant changes in precipitation levels and the timing of snowmelt in the Sierra Nevada?
- What hydrological variables should be monitored to improve our understanding of the state's natural and managed water systems?

PIEREA is recommending the following research to address those questions:

Monitoring of Hydrologically Important Variables

As noted in the previous section, PIEREA in conjunction with other state agencies, would conduct regular, consistent and sustained measurements of hydrologically important variables such as precipitation, snowpack, and streamflow, to track changes in these variables and to verify model predictions. Monitoring would focus on locations where significant change is expected (e.g., mountain snow zones) and locations where additional measurements could enable researchers to analyze important processes. **Benefits:** Improved understanding of important hydrological

[3] A model's *domain* is the area being modeled.

processes and being able to detect and interpret climate change signals as early as possible. (The latter goal would require a long-term monitoring program that should be supported by PIEREA, but conclusive results should not be expected during the implementation period of this plan.)

Testing the Operation of the State Water System under Plausible Climate Scenarios

In conjunction with the Department of Water Resources, this project would study the state water system, with an emphasis on the operation of the Central Valley Project and the State Water Project, which together furnish about 30% of California net water demand for agricultural and urban uses. The major reservoirs of these two projects are located on watersheds likely to see large shifts in runoff patterns as a result of rising snow levels. This work would draw upon approximately 50 years of monthly hydrology data, to include simulations during the two major six-year historical droughts (1928–1934 and 1987–1992) and the climate scenarios mentioned above. It could involve modification of the CALSIM model (used for state water planning) and the CALVIN model (an economic-engineering optimization model of California's water supply system that identifies optimum operation conditions) for climate change studies. This work would also expand upon the "INFORM" demonstration project, currently funded by PIEREA, which is analyzing the application of modern hydrological forecasting and decision analysis methods to the operation of several California reservoirs. **Benefits:** The state would have the ability to study the impact of climate change on the availability of water for agricultural, urban, industrial, recreational, and environmental purposes; and conduct scenario studies of a large portion of its water system.

Impacts of Climate Change on Ecological Resources

Land use changes and vegetation patterns may have a strong effect on regional climate and the hydrological cycle, both at the global and regional levels. Of course, climate also affects vegetation patterns; therefore, they form a complex, interacting system. Changes in vegetation patterns and hydrology will, in turn, impact energy demand and the availability of hydropower. Policy and decision makers need to understand how these factors will affect California if they are to make informed decisions about the use of the state's land, water, and other natural resources. These issues involve a range of research questions that exceeds the availability of PIEREA resources for support. PIEREA's approach would be to provide "seed money" to address the following questions, while working actively to generate additional funding from other sources to expand work on ecological impacts in California:

- What are the potential changes in vegetation patterns in California, and how would they affect and be affected by the state's climate and the hydrological cycle?
- How would urban development and climate change affect vegetation patterns in California? Would urban areas impede the migration of species, and therefore be a dominant feature determining vegetation patterns?

PIEREA is recommending the following research to address those questions:

Enhancement and Application of Dynamic Vegetation Models (DVMs) for California

Building on previous PIER-funded DVM work, this project would explore ecosystem responses to multiple global changes and identify trends that would affect California ecosystems through the use of ecosystem models that incorporate unexploited or new field data. Researchers would enhance DVMs to evaluate the effects of: land use (e.g., the impacts of current land use, land use change, land cover fragmentation, the history of land management on ecosystem dynamics, and migration corridors); vegetation age structure; species dispersal rates and modes (for a few target species); and non-native invasive species and introduced pest pathogens. The DVMs should also consider the impact of other stressors (such as air pollution) and be used with regional climate models to investigate the interaction between climate and vegetation. This work should be coordinated with field studies and provide seed funds for additional field studies, if necessary. **Benefits:** DVMs that model interactions between a greater number of critical ecosystem factors would improve understanding of the impacts of each factor and of the interrelated systems. These models could also enable researchers to identify and interpret ecological trends more readily.

Carbon Sequestration in Terrestrial Ecosystems and Geological Formations

In September 2002, the legislature required the California Climate Action Registry[4] to allow the registration of carbon reductions produced by the sequestration of carbon in forested lands or by reforestation. Terrestrial ecosystems offer significant potential to capture and store carbon at modest costs, providing multiple social benefits. PIEREA-supported projects would address the following questions:

- What would be the costs associated with carbon sequestration projects in the state? How much carbon would they be able to sequester? What areas are the best sites for these projects?
- What are the potential social, economical, and environmental impacts associated with the most promising carbon sequestration options in the state?
- What would be the role of bioenergy in any efforts designed to reduce GHG emissions from in-state sources?

PIEREA is recommending the following research to address those questions:

Development of Cost Estimates for Forestry and Agricultural Soil Carbon Sequestration Options in California

Understanding the potential for carbon sequestration in soil in California requires careful estimation of the costs of various specific sequestration options. The development of such estimates for forestry strategies in California would enhance ongoing PIEREA/California Department of Forestry and Fire Protection (CDF) work by adding field measurement studies and performing a detailed analysis for one or two counties in California, to generate more precise cost estimates and more realistic estimates of carbon sequestration potential. Research on agricultural soil carbon sequestration would identify agricultural carbon sequestration opportunities. In conjunction with

[4] This is a non-profit organization created by the state legislature to allow companies to register their annual GHG emissions for potential consideration in any regulatory scheme that may evolve in the future.

the CDF, researchers would conduct field studies of promising management practices, evaluate models of carbon and nitrogen budgets and carbon sequestration , and estimate the costs and carbon sequestration opportunities for the selected county(ies), based on a validated model(s). PIEREA would also fund some work regarding unresolved monitoring and verification issues. **Benefits:** An economic assessment of forestry and agricultural soil carbon sequestration strategies would help decision makers prioritize those strategies, and also help agricultural and forestry specialists who are involved in allocating resources among competing alternatives.

Economic Studies of Bioenergy Strategies in California

This project would complement PIER-funded renewables research by conducting analytical studies to identify obstacles in the deployment of bioenergy technologies, and improve understanding of the private and social costs associated with the use of bioenergy projects as a GHG emissions-reduction tool. The effort could: (1) Collect and analyze costs to farmers and foresters on energy crop cultivation in California (including collection, processing, and distribution costs); (2) conduct life-cycle assessments of bioenergy strategies in California;[5] (3) study the economics of biorefineries, to reduce the costs of biomass collection and transport in California; (4) study the economic feasibility of using urban carbon-based residuals for bioenergy production; (5) develop models of broad-scale biobased products and bioenergy market development; and (6) develop models of rural development that would support biomass production, processing, and use. **Benefits:** A comprehensive understanding of the feasibility and economic factors involved in bioenergy use in California, and potential solutions for overcoming barriers to the use of bioenergy in the state.

Carbon Sequestration in Geological Formations

This project would support research designed to address the major technical issues associated with geologic storage in California. Research topics include: (1) monitoring and verification; (2) risk assessment, human health and environmental impact; (3) tectonic stability; (4) economic analysis/viability of technologies; (5) leakage assessment and petroleum reservoir analogues; (6) performance assessment; and (7) evaluation of novel technologies. PIEREA also proposes to support the development and demonstration of storage technologies through collaborative field demonstrations. Candidate technology demonstrations include: enhanced oil recovery, optimized for CO_2 storage; enhanced gas recovery, optimized for CO_2 storage: disposal in deep saline formations; and disposal accompanying subsidence mitigation. A second parallel activity would address CO_2 sources and storage infrastructures. Research needs to characterize present and potential CO_2 sources and assess compression, pipeline, and injection well infrastructure needs. PIEREA would provide seed money for this effort, but substantial outside funding is needed for the complete execution of this project. **Benefits:** Identification and quantification of the feasibility, economics, and potential of various strategies for sequestering carbon in geological formations would help decision makers prioritize options. Implementation of this carbon sequestration option could result in enhanced recovery of oil and gas from California oil/gas fields.

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[5] This work would be coordinated with other life-cycle analyses identified in the PIER Environmental Area Research Plan. Life-cycle assessments for other carbon sequestration strategies may be conducted.

Greenhouse Gas (GHG) Reduction Curves and Inventory Methods

"Supply curves" have been used for many years to graphically display, in simple terms, the cost and availability of a resource or other market good. "Greenhouse gas reduction curves" work in a similar way—illustrating the cost and effectiveness (in terms of GHG reduction) of various GHG-reduction strategies. As shown in Figure 2, the curve's vertical axis represents the cost of each GHG reduction strategy (per unit saved), and the horizontal axis represents the quantity of units saved or avoided. Measures are ordered on a marginal, least-cost basis. To conduct sound evaluations of GHG-reduction measures, these curves must be expanded to include longer time horizons, technological advancements, and non-energy cost and benefits. In addition, there is a need for better data to resolve the uncertainties in GHG emission inventories, so that emissions trends can be tracked more accurately.

PIEREA-supported projects would address the following questions:

- What are the costs associated with reducing GHG emissions in other sectors of the economy, in comparison to those of reducing GHG emissions from the electricity sector?
- What emission estimation methods should be improved to better characterize GHG emissions and GHG emission reduction opportunities?
- What methodological features should be enhanced to improve the usefulness of supply curves for policy analyses and for their consideration in macroeconomic analyses?

PIEREA is recommending the following research to address those questions:

Energy Balances for California

Currently available energy balances for California, which are used to estimate multiple emissions from a variety of sources, require further refinement to ensure that all pertinent fuel information is included, to achieve an appropriate level of disaggregation for state-level analysis, and to correct certain inaccuracies and inconsistencies. PIEREA would fund the development of California energy balances at the highest possible level of spatial and temporal disaggregation. Researchers would also perform a critical review of existing fuel consumption data for all power plants in the state. **Benefits:** Accurate data would be available in a form that researchers can use to improve estimates of energy consumption and CO_2 emissions from the combustion of fossil fuels in California, and more data would be available for economic analyses.

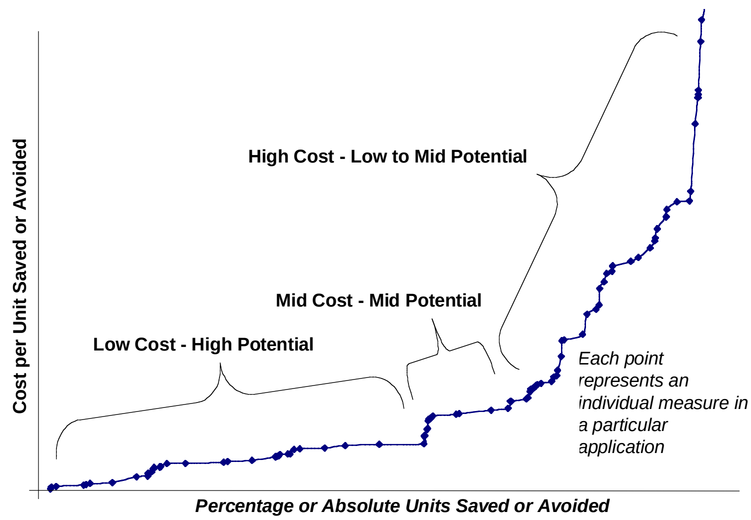


Figure 2. Example GHG-reduction Supply Curve

Research on New, Improved Methods to Estimate Non-CO_2 Emissions

Research has attempted to determine the level of uncertainty in the existing non-CO_2 GHG emissions inventories by assigning probabilities to the range of potential parameters in the equations that are used to estimate emissions. However, in some cases, the basic equations or methods used to estimate emissions do not incorporate all the parameters necessary to do so adequately, thereby rendering the results incorrect. Problems with the existing methods also cast doubt on the reported trends in official GHG emissions inventories. This project would: study the level of uncertainties associated with different emissions sources; identify potential new sources not being considered in existing inventories (such as the state strategy of composting to reduce waste volumes because existing methods assume that composting does not generate emissions); and prioritize which methods to study in detail with field studies and/or model development work. **Benefits:** Standardized methods to estimate non-CO_2 emissions could be developed, based on more comprehensive, California-focused data. Accurate estimates are necessary for the development of sound emission reduction options.

Development of Supply Curves for California

This research would be coordinated heavily with the inventory methods development work, and would study and implement a number of methodological and macroeconomic integration issues. Based on studies developing short-term supply curves for California for the electricity sector, PIEREA would develop methods to extrapolate them to much longer time horizons that account for potential technology changes. This project would also develop curves that identify adoption barriers of various options included in the supply curves and their effect on the actual performance of the different options. This process would include the consideration of non-energy costs and benefits that are traditionally not quantified in the development of these curves. PIEREA would also develop the information needed to include the options identified in the supply curves studies in macroeconomic analyses. **Benefits:** Dynamic supply curves that researchers can use to estimate the long-term costs and benefits of GHG-mitigation measures, over a larger portion of the economy, to make direct comparisons between competing options.

The Economics of Climate Change Mitigation and Adaptation in California

Economic methods are the primary tools for evaluating the socioeconomic implications of climate change and the costs and benefits of policy responses. Economics is also the primary disciplinary source of theoretical and computational tools for integrating climate science and policy. Several decades of research on the economics of climate change at the national and international levels, as well as PIEREA-supported recent work specific to California, provide a foundation for new PIEREA-sponsored research on the economics of climate change in California. PIEREA-supported projects would address the following questions:

- How will the impacts of climate change and measures to abate GHGs affect the California economy in the coming decades?
- What are the key economic risks for California from climate change, and what are the particular risks from abrupt and/or extreme climate change?
- How will climate change affect the state's integrated water/agricultural system, and what will be the costs and benefits of policies to address potential impacts on this system?
- What are the costs and benefits of both price and non-price-based policies designed to increase energy efficiency in the California economy, and how are they influenced by energy-related technological change?
- How should California design regional markets for emissions trading?
- How should GHG-abatement and air quality policies be integrated?
- What are the costs of abating non-CO_2 GHGs?

PIEREA is recommending the following research to address those questions:

Integrated Modeling and Impact Analysis

In energy and climate applications, economists use computable general equilibrium (CGE) models to estimate the costs of price-based policies (e.g., carbon or energy taxes, or tradable emissions permit systems) to reduce GHG emissions—as well as the costs of climate change impacts. This PIEREA project would modify and significantly enhance a CGE model of California, in order to estimate the potential impacts of climate change and GHG mitigation policies on the state economy. Researchers would also analyze the potential for California to use proceeds from measures to improve the state's fiscal balances ("revenue recycling"). Further, they would design and support the development of a new modeling framework to analyze the economics of climate change in California that would account for risk and uncertainty. Both the CGE modeling and new decision-analysis framework would be used to integrate and apply findings from new PIEREA research on the sector-specific impacts of climate change in California. This work would develop a large range of plausible scenarios for the future regional climate evolution.

PIEREA would focus research addressing abrupt and/or extreme climate change, institutional factors, and realistic decision rules on California's water and water-related sectors, which are perhaps the major pathway through which climate change will affect the state's economy. In California and neighboring states, a major pathway by which increased climate variability and change will affect the society and economy of the region is through the impact on streamflow within the region and on the regions' developed water supply. Any change in the developed water supply will have important consequences for the allocation of water between agricultural water users, urban water users, hydropower generation, and in-stream uses of water for water-based recreation and ecosystem services. Each stakeholder group may face increased costs and/or reduced benefits as the result of a reduction in the reliability of water availability.

This research would assess the impacts on each sector from changes in water supply reliability. Researchers will develop quantitative and explicitly probabilistic measures of water supply reliability for agricultural and urban water users at different California locations, using existing climate conditions, and basing assessments on the state's water system operation over the past 20–30 years. Researchers will use these measures to develop sets of marginal benefit functions that show the incremental benefit or losses associated with changes in water supply reliability for agricultural users, urban users, and hydropower generation at various locations around the state. This analysis will utilize the empirical measures of supply reliability for agricultural and urban users described above. A third research component will develop projections and analyses of water use and electricity demand, taking account of location and housing density. PIER research will estimate both the monetary and non-monetary magnitudes of these impacts, incorporating several methodological innovations that will reflect the research priorities described above: explicit treatment of the surface water supply system, inclusion of regulatory and legal constraints on the existing process for water allocation, and representation of the actual decision rules employed in California's water system. **Benefits:** This effort would provide a benchmark for further work and a first assessment of the possible aggregate economic impacts of climate change and GHG policy on California. The state CGE modeling effort would provide an initial integrating framework that would incorporate results of the PIEREA research on water and agriculture, energy demand, technological change, and other key areas. In addition, this research would provide improved theoretical and empirical tools for understanding the potential impacts of climate change on California's integrated water/energy/economic system, as well as the costs and benefits of potential adaptation and mitigation measures associated with this system. Ultimately, this work would enable policy-makers to develop robust strategies in response to uncertain climate, economic, and technological change.

Energy Efficiency and Technological Change

Because California's energy system will be a major focus of any future carbon mitigation policies, PIEREA-sponsored research would improve policy-relevant methodologies for estimating carbon abatement costs, which would provide California's policy-makers with improved tools for implementing carbon mitigation policies. This research would be integrated with PIEREA's GHG-reduction-curve research. First, research would focus on the degree to which energy-efficient technology is optimally allocated by markets in the absence of policy intervention, because such policies will almost certainly form a major component of California's carbon mitigation efforts. According to standard economic models, the benefits of these policies cannot exceed their costs, which is a quandary demanding careful attention from economists and technology researchers. Researchers would evaluate the literature to determine the robustness of sources and data quality, the soundness of the theoretical models employed, and the role of assumptions regarding market structure. Based on that evaluation, they would develop new models of consumers' and firms' efficiency-related choices, in the context of behavioral economics. Further, research would measure and model energy-related technological change, which affects cost estimates of reducing energy demand or carbon emissions. Researchers would also develop case studies on selected state industries to model and measure learning-by-doing and its relation to other key parts of the industrial innovation process, such as the adoption and diffusion of new technology. They would also study ways of incorporating both endogenous technological change and learning-by-doing in the program's CGE modeling and in the new computational modeling framework that would be developed. As part of this effort, PIEREA would seek co-funding to study how information technology may affect California's energy system and its response to carbon abatement policies, and incorporate the results of this work in the CGE and further aggregate modeling sponsored by PIEREA. **Benefits**: This project would help improve understanding of the role of energy efficiency in reducing GHG emissions by quantifying benefits and costs from these measures and exploring the optimal implementation and use of energy efficiency technologies for this purpose.

Non-CO_2 GHGs and Markets for Emissions Trading

A number of policies to control CO_2 emissions would also reduce emissions of other pollutants, with important implications for regional air quality. It is important to integrate CO_2 with other GHGs when devising mitigation strategies—both to reduce costs through the achievement of multiple benefits, and to achieve more benefits more rapidly. In this project, PIEREA would support research to develop a multi-GHG approach that fully exploits potential synergies and reaps ancillary benefits. Simultaneously, PIEREA-funded research would improve the methodology for constructing marginal cost or supply curves for non-CO_2 greenhouse gases, in order to develop a theoretical model that allows for empirically verifiable negative cost abatement and cost-reducing technological change. This work would be integrated with the PIEREA-funded development of GHG-reduction curves. In addition, because emissions trading has emerged in recent years as a favored instrument for reducing GHG emissions, PIEREA would sponsor a study on the feasibility of developing a California intrastate trading market. This study would examine the appropriate geographical and sectoral scope, which GHGs would be included, the required institutional mechanisms, and related elements. The goal would be to determine the appropriate elements of a regional trading market, whether implemented as a stand-alone state response to climate change or in response to national or international agreements. **Benefits:** Multi-GHG reduction strategies would expand and speed air quality benefits, at a lower overall cost. Development of a regional GHG trading market could also speed GHG-emissions reduction.

PIEREA: Supporting Informed and Systematic Planning for Climate Change

In developing this research plan, the California Energy Commission is responding to a broad range of important issues related to the development of effective responses to climate change. Research that provides a foundation for policy and investment decisions in the state is of critical importance, and PIEREA has developed this collaborative climate change research program to meet those needs. PIEREA's intention is to produce a comprehensive report, integrating the results of the research described above, approximately five years following the inception of this research program.

In considering appropriate strategies to deal with climate change, we must consider the nexus among mitigation strategies, sensitivity to changes, capacity to change or adapt, and vulnerability to change. These factors will inform cost/benefit estimates and the social and political assessment of risk acceptability. Ultimate action will also be driven by a sense of ethics and morals.

Moreover, economic activities, the physical infrastructure, and natural systems in California are inextricably linked. A good understanding of the dynamics of these systems is essential, as is a clear sense of their interrelationships. These concepts apply as much to business enterprises as they do to ecosystems. The goal of California decision-makers and stakeholders should therefore be to craft investment and policy strategies to maintain ecosystem health, productive capacity, and quality of life. These decisions must in turn be based on an accurate scientific understanding of the issues. To the extent that we are learning and living by "adaptive" management, we need to maximize the level of resilience in California's natural and engineered systems.

The PIEREA climate change research program is designed to support this important challenge.

1. Background and Overview

Climate change is no longer a hypothetical or distant possibility—it is occurring, and is likely to have a profound impact on human society and the natural environment over the coming decades. Climate change and its impacts on a global scale are the focus of an intense, broad-based international research effort in the natural and social sciences. Understanding the nature and potential consequences of climate change on regional scales, however, and for California in particular, is a challenge we have just begun to meet. This research plan has been prepared by the California Energy Commission to contribute to California's intensifying efforts to understand how climate change will affect the state's social, economic and natural systems, and to help provide policy-makers with the knowledge and tools they need to anticipate and plan for these impacts.

This opening section of the research plan discusses the role of CEC's PIER program in climate-related research, summarizes the development process for this plan, outlines the relations between PIER and other state agencies in conducting climate change research, and summarizes key benefits of the research proposed here.

1.1 The PIER Role in Climate Change Research

The scientific and analytical study of climate change and its potential impacts on California's economy and natural environment is one of the many areas of focus for the Energy-Related Environmental Research area of the PIER group (PIEREA). This *PIEREA Climate Change Research, Development, and Demonstration Plan* was prepared by PIEREA to provide a comprehensive vision of how it intends to support climate change research in California.

There are three primary reasons for a major PIER research effort on climate change. First, electricity generation in, or for import into, California is a major source of greenhouse gas (GHG) emissions. Therefore, PIEREA, according to its mission, must undertake climate change research at the state level, to evaluate and suggest means of mitigating the climate-related effects of electricity. Second, there is a high likelihood that climate change will have a significant, direct impact on the consumption of energy—and particularly electricity—in California because of changes in temperatures within the state. Accordingly, PIER must investigate how the state can prepare for and adjust to these changes in electricity demand. Third, by altering precipitation patterns across the West, climate change is likely to affect the supply and cost of hydropower, which represents about 20% of in-state electricity generation. Thus, it is necessary for PIER to determine how to accommodate these hydropower impacts, in order to maintain reliable and affordable energy flows to California's households and businesses in the context of a changing regional climate.

The research proposed in this Plan will build upon the long-standing contribution of the California Energy Commission (Commission) to climate change policy formulation in California. In 1988, the California Legislature (Assembly Bill 4420, Sher) directed the Commission to begin a study of the potential impacts of global warming trends on the state's energy supply and demand, economy, environment, agriculture, and water supplies, and to develop policies for reducing these impacts. The Commission prepared a report in cooperation with other concerned state agencies and submitted this report to the Legislature on November 1991 (CEC 1991). Similarly, in 1997, the Commission staff prepared for the U.S. Environmental Protection Agency an inventory of GHG emissions and an evaluation of potential policies and strategies for reducing GHG emissions in the state (California Energy Commission 1998). Recently, SB 1771 and its subsequent revisions require, among other things, that the Commission update the statewide GHG emission inventory every five years and "…convene an interagency task force consisting of state agencies with jurisdiction over matters affecting climate change to ensure policy coordination for those activities." This bill also requires the Commission to establish a climate change advisory committee to make recommendations to the Commission on the most equitable and efficient ways to implement any national or international requirement on climate change (CEC 1998). There is a need for a strong, unbiased climate change research program that informs the policy debate without advocating a particular position on any issues. PIER climate change research will strive to play this role, which is in accordance with the PIER program's legislative mandate and in agreement with the adopted mission of the PIEREA area.

1.2 Development of the PIER Climate Change RD&D Plan

Research on global climate change and its social and economic impacts is a very active and expanding focus at many universities, government agencies, and other institutions around the world. However, relatively little of this work addresses the significant scientific or policy questions related to climate change that are of unique importance to California. PIER is currently funding several studies that address climate change as it relates to California, to begin building the knowledge base needed by state policy-makers. (These studies and their implications for this plan are described subsequent sections.) To help determine how to expand upon and extend this work, PIEREA commissioned research roadmaps on various topics related to climate change, to identify research gaps that would be important to the state but would most likely not be addressed by existing national and international research efforts. Technical experts on climate change issues or closely related areas prepared these roadmaps with input from a large group of researchers from a range of disciplines.

The roadmaps are expansive, in the sense that they cover research topics well beyond those that could be addressed feasibly by the PIER program, but they were developed to identify and prioritize research areas based on their overall importance and relevance to PIEREA goals. The breadth of the roadmaps also allows the PIER program to more easily identify areas of common interest with other research programs. In some cases, other research entities are using these roadmaps to identify research opportunities. For example, the California Department of Water Resources (DWR) is using the roadmap on water resources to identify preliminary areas of work on climate change for inclusion in the 2003 State Water Plan. The DWR plan is a major effort undertaken every five years that, for the first time, will take into account climate change concerns. The California Assessment Report (Wilkinson et al. 2002) also used these roadmaps to suggest research priorities to the national research program on climate change.

Although this research plan is based primarily on the roadmaps commissioned by the PIER program, the limited funds available for the implementation of the PIER program on climate change are not sufficient to fund all the research needs identified in the roadmaps. Thus, this plan identifies the areas of research that have been selected as priorities for PIER research funding according to the criteria of: (1) relevance to PIER objectives (i.e., concerning the energy sector), (2) likelihood of generating scientifically and/or policy-relevant results within no more than four-to-five years, (3) potential applicability to California policy-making related to climate change, (4) technical quality and potential to advance scientific understanding, (5) potential to generate "co-benefits" (i.e., in science or policy not directly related to climate change), (6) likelihood of eventually securing co-funding from other agencies, and (7) the clear need for state support to reach the level of funding necessary to address these issues adequately. The Plan emphasizes the following themes: cooperation with other agencies when conducting research; concentration on projects that will achieve multiple benefits and are policy relevant; advancement of science and knowledge; and identification of "no regrets" opportunities, which are actions that benefit California even in the absence of climate change considerations.

The following is a list of the roadmaps and the technical experts responsible for their preparation:

- Ecological Impacts of a Changing Climate (Rebecca Shaw, Stanford University)
- The Effect of Global Climate Change on California Water Resources (Maurice Roos, California Department of Water Resources)
- The Economics of Climate Change Mitigation and Adaptation in California (Alan H. Sanstad, Lawrence Berkeley National Laboratory)
- Modeling Regional Climate Change in California (Larry Gates, Lawrence Livermore National Laboratory)
- Developing Greenhouse Gas Supply Curves for In-State Sources (Mike Rufo, Xenergy, Inc.)
- Carbon Sequestration in California's Terrestrial Ecosystems and Geologic Formations (Ed Vine, University of California, Office of the President and Mark Wilson, Consultant)

These experts benefited from generous input from technical representatives of multiple state agencies (i.e., the California departments of Water Resources, Food and Agriculture, Forestry and Fire Protection, and the Air Resources Board); researchers from the University of California, California State University, and other universities; national laboratories; environmental groups; federal agencies; the Electric Power Research Institute; electric utilities; California irrigation districts; the California Climate

Registry; and the United States Global Change Research Program. The roadmaps are available from the California Energy Commission as separate documents. PIEREA may commission the preparation of additional roadmaps in other areas, such as the study of the potential impacts of climate change on public health, agriculture, and forested areas. This work will be conducted with the full cooperation with the relevant state agencies.

In addition to identifying priority areas for PIER funding, this document considers the interactions among different research areas to produce a comprehensive research plan. It presents a relatively long-term research agenda (20 years), but it focuses on the research activities that should be funded in the next two years. Individual products will be generated on a continuous basis, but PIEREA's goal is to produce an integrated report in four or five years, after all the elements identified in this plan have been executed. The plan is a living document that will be revised and updated regularly to reflect continuing scientific progress. In addition, since one of the goals of this plan is to identify policy-relevant research, this plan will be updated as needed to consider policy developments at the state, national, and international levels.

1.3 Coordination and Cooperation with Other State Agencies

A number of research activities are in progress at various state agencies that, while in most cases undertaken for other reasons, have implications for understanding climate change and possible policy responses. For example, the California Air Resources Board (ARB) efforts to understand the formation, transport, and deposition of aerosols (small particles) in the air is of relevance for climate change research, because aerosols are important drivers of climate change at the regional and global levels (Hansen 2001, Menon 2002). Aerosol research could have significant implications for climate policy because it indicates that black carbon (i.e., soot) should be considered a contributor to global warming; further confirmation of this finding would suggest that measures to reduce its atmospheric concentrations could be folded into climate change mitigation efforts. Similarly, the forest inventory work of the California Department of Forestry and Fire Protection is directly relevant to any efforts designed to estimate the amount of carbon stored in terrestrial ecosystems in the state. Other state agencies (e.g., the Department of Food and Agriculture and Department of Water Resources), state-federal partnerships such as CALFED, and funding programs such as the Kearney Foundation of Soil Science are also conducting climate-change-relevant studies that must be considered in the preparation and implementation of any research plan on climate change for the state.

As noted earlier, PIEREA is also already funding some studies on climate change and has engaged different state agencies on these studies. For example, technical staff from the Department of Water Resources (DWR) and the Department of Food and Agriculture have provided invaluable technical support for a study being conducted by researchers with the University of California at Davis looking at the potential impacts of climate change on water resources and hydropower production in particular. In fact, DWR will consider this study in the preparation of its 2003 State Water Plan.

PIER's role in climate change research will be one of cooperation and coordination with other state and federal agencies, research programs, and funding agencies to avoid duplication of efforts, to leverage limited resources, and to ensure the production of high-quality, policy-relevant research for California and the nation. PIEREA will fulfill this role by seeking the input of different stakeholders in the execution of this research plan, and by organizing regular scientific workshops and conferences on climate change where the work funded by PIEREA and others will be presented, with the goal of sharing results and seeking cooperation. PIEREA will continue to work with other state agencies to develop joint research projects as much as possible, as has been done so far with the California Department of Forestry and Fire Protection (CDF) and DWR. Finally, PIEREA will actively seek cooperation with other research programs and funding agencies to enhance research on climate change in California. For example, PIEREA is currently in contact with the Kearney Foundation, the National Oceanic and Atmospheric Administration (NOAA), and the U.S. Department of Energy (DOE) in order to develop projects of common interests that are also compatible with this research plan.

1.4 Key Benefits

The research outlined in this plan is an interrelated group of projects whose ultimate benefits not only address climate change issues in California, but also improve the overall health and vitality of the state's citizenry, environment, and economy. Some projects yield these benefits directly; whereas, others serve as inputs to other efforts that deliver direct benefits. All research efforts were evaluated on their ability to deliver benefits beyond those associated with climate change.

The lists below identify some key benefits in each subject area. Each topic's subsection in Section 3 discusses benefits in more detail.

Climate Change Sensing and Modeling

- Greatly improved and comprehensive understanding of likely regional climate changes that will affect California's hydrology, agriculture, and natural ecosystems
- Better snow-level forecasting and detection of subtle climatic changes
- Improved models based on higher-quality and more comprehensive data
- Better understanding of energy consumption patterns and climate, including the effects of urbanization
- Standardization of modeling protocols

Impacts of Climate Change on California Water Resources

- Improved understanding of important hydrological processes and capacity for early detection and interpretation of climate change signals
- Projections of the impacts of climate change on the availability of water for agricultural, urban, industrial, recreational, and environmental purposes in California

Impacts of Climate Change on Ecological Resources

- Increased representation (in dynamic vegetation models) of interactions among critical ecosystem factors, improving understanding of the impacts of climate change on each factor and of the interrelated systems
- Enhanced capability for identifying and interpreting ecological trends

Carbon Sequestration in Terrestrial Ecosystems and Geological Formations

- An economic assessment of forestry and agricultural soil carbon sequestration strategies to help decision makers prioritize those strategies, and also to help agricultural and forestry specialists allocate resources among competing alternatives
- A comprehensive understanding of the feasibility and economic factors involved in bioenergy use in California, and potential solutions for overcoming barriers to the use of bioenergy in the state
- Identification and quantification of the feasibility, economics, and potential of various strategies for sequestering carbon in geological formations, to help decision makers prioritize options

Inventory Methods and Supply Curves

- Accurate data in a form that researchers can use to improve estimates of energy consumption and CO_2 emissions from the combustion of fossil fuels in California, and for use in economic analyses
- Standardized methods to estimate non-CO_2 emissions, based on more comprehensive, California-focused data

The Economics of Climate Change Mitigation and Adaptation in California

- A first assessment of the possible aggregate economic impacts of climate change and GHG policy on California, and analytical and empirical benchmarks for further study
- An integrated modeling framework for incorporating results of PIEREA research on water and agriculture, energy demand, technological change, and other key areas
- Tools to enable California policy-makers to develop robust strategies in response to uncertain climate, economic, and technological change
- Improved understanding of the costs and benefits of increased energy efficiency in reducing GHG emissions in California
- Identification of multi-GHG reduction strategies that could also generate air quality benefits, at a lower overall cost
- Assessment of potential for regional GHG trading markets in California

1.5 PIEREA Climate Change Research Plan Organization

This research plan is organized as follows: Section 1 has outlined PIER’s role in climate change research, the plan’s development process, and key research benefits. Section 2: *Climate Change and California* provides a brief overview of facts regarding global climate change, key mechanisms of climate change in California, possible impacts, and a profile of the state's GHG emissions. Section 3: *PIEREA Research Agenda and Benefits* outlines PIEREA's proposed research activities and the benefits that will accrue from their implementation. Section 4: *Bibliography* lists the references used to prepare this plan.

2. Climate Change and California

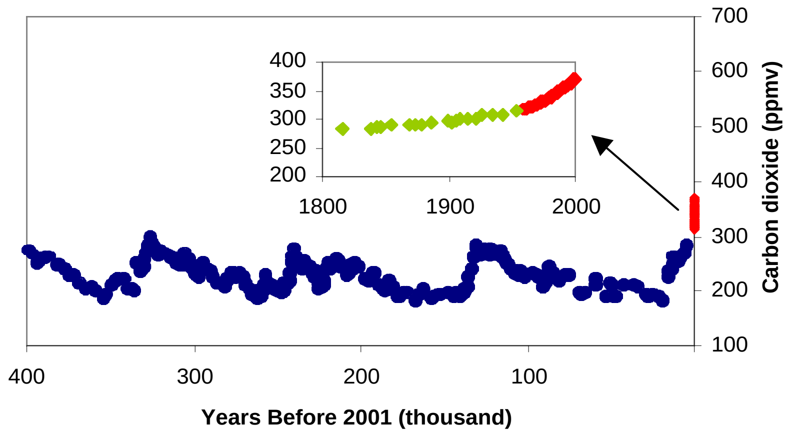
2.1 From Global to Regional Climate Change

There is now a broad scientific consensus that the global climate is changing in ways that are likely to have significant socioeconomic consequences, and that these changes will continue and probably intensify through the twenty-first century. Climate change research findings have been detailed by the authoritative International Panel on Climate Change (IPCC). In its Third Assessment Report (TAR), released in 2001, the IPCC concluded that the increase in the global average surface temperature during the twentieth century "…is likely to have been the largest of any century during the past 1,000 years." Moreover, the modeling studies considered by the IPCC project that this temperature will increase by 1.4 to 5.8°C (2.5 to 10.4°F) over the period 1990 to 2100.

There is also mounting evidence that observed global climate change is due substantially to human activities—specifically the emissions of greenhouse gases (GHGs) such as carbon dioxide, methane, and nitrous oxide. The IPCC Second Assessment Report (SAR), released in 1995, indicated that "The balance of evidence…suggests a discernable human influence on global climate." (IPCC 1995). The TAR contains a much stronger conclusion: "There is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities" (IPCC 2001). A recent report prepared by the U.S. National Academy of Science at the request of the Bush Administration confirms this finding (National Research Council 2001).

Studies of the paleoclimatic record indicated a link between changes in the atmospheric concentrations of GHGs and changes in climate. Figure 1 shows how ambient concentrations of carbon dioxide (CO_2), the most important GHG, in the atmosphere have changed in the last 400 thousand years. The increase of fossil fuel consumption since the industrial revolution has resulted in a rapid increase of atmospheric concentration of this gas. In fact, twentieth century concentrations are the highest in the last 400 thousand years, as illustrated in the figure.

The results of ongoing scientific research are reinforcing the conclusions of the TAR. For example, scientists from Scripps Institution of Oceanography recently analyzed data that was collected since 1950 on changes in ocean temperatures at depths up to 3,000 meters, to detect and attribute observed climate changes (Barnett, David et al. 2001). The resulting report concludes that "the observed ocean heat-content changes are consistent with those expected from anthropogenic forcing, which broadens the basis for claims that an anthropogenic signal has been detected in the global climate system." (ibid.).



Data Sources: Keeling 2002, Barnola 1999.

Figure 1. Changes in Atmospheric CO_2

Moreover, recent studies of the uncertainty in projected potential changes of average global temperatures during the coming century suggest that the results reported in the TAR may understate the possibility of strong warming (Knutti, Stocker et al. 2002). The new results, obtained making systematic changes to the model parameters (within plausible ranges) while ensuring that the modeling results are still consistent with the recent observed warming, indicate a higher likelihood of warming in the upper end of the range reported by the IPCC, when emissions are as projected in the "B1" SRES scenario (Nakicenovic 2000).[6]

Indeed, research at the frontiers of atmospheric science, on the underlying mechanisms of the climate system, is providing even greater reason for concern regarding the potential character of climate change in the coming decades. Until quite recently, virtually all research on climate change—both scientific and socioeconomic—has focused on scenarios of gradual, smooth shifts, primarily as measured by long-run equilibrium increases in mean global surface temperature. There is, however, growing attention within the scientific community to the possibility that increased concentrations of GHGs may induce abrupt and discontinuous shifts in the climate system on much shorter time scales (National Research Council 2002). Recent scientific evidence shows that widespread major changes in climate have occurred in our planet and that these changes took place with startling speed (i.e., decades or even years). The socio-economic impacts of abrupt climate change would almost certainly be much greater than those of gradual, long-run shifts.

[6] The B1 scenario in the IPCC's *Special Report on Emissions Scenarios* emphasizes "…a high level of environmental and social consciousness combined with a globally coherent approach to a more sustainable development."

In moving from a global to a regional scale, the possibility of abrupt climate change becomes even more salient. Understanding of global climate trends does not directly translate to the regional scale that is of concern for California, and regional climate modeling and analysis is much less developed than global. Our ability to foresee precisely how global climate change will impact California's climate is accordingly limited. However, the character of climate change in California may be much more in the nature of abrupt shifts, greater variability, and an increased number of "extreme events" such as droughts and floods than the long-run smooth changes in trends that have been the focus of much global-level analysis. Moreover, anthropogenically induced climate change affecting California directly will both be superimposed upon, and interact with, existing natural patterns and variation in the regional climate. For these reasons, anticipating California-specific climate change impacts is more a challenge of assessing risks and uncertainties than of making specific predictions. Nevertheless, enough is understood regarding the regional climate to anticipate *possible* impacts, and in certain cases, relate them to present day trends. These issues are discussed in the following section.

2.2 Pathways of Climate Change in California

As noted above, climate change in the coming century will probably not happen slowly, whether at the global or the regional scale. The observed and reconstructed climate record is replete with examples of how various climate elements have shifted suddenly and strongly. We can expect the climate to undergo a rich variety of changes in the next century, as natural changes add to (and perhaps interact with) changes brought on by anthropogenic climate change. From either source, however, it is important to recognize that California's complex natural and socioeconomic systems are already susceptible to climate variability and change with climatic events such as El Niño (described below), floods, mudslides, coastal erosion, droughts, fires, and heat waves affecting the state's economy and quality of life. This section will discuss some of the factors that affect California's climate and the effect that the climate has on weather patterns in the state. For a more thorough overview of the observed and projected impacts of climate change on California, consult *Confronting Climate Change in California* (Field, Daily et al. 1999), *Climate Change Impacts on the United States* (USGCRP 2001), and *Preparing for a Changing Climate: The Potential Consequences of Climate Variability and Change: California* (Wilkinson et al. 2002).

California's proximity to the Pacific Ocean, the long axis of the state (which straddles latitudes from just beyond the subtropics northward to the temperate latitudes), and its diverse topography (which produces a variety of drastically different microclimates) combine to produce a unique climate with complex weather patterns.[7] Because of this

[7] For clarification, the term c*limate* pertains to the aggregate distribution of the weather at a given locale, including its statistical properties such as averages and extremes. W*eather* consists of the day-to-day events such as sun, rain, fog, warm, cold, and wind. Although climate can vary from year to year, we expect some state weather trends (i.e., warmth in the summer and rain in winter) to be relatively predictable. However, growing evidence is showing that those expectations may no longer be as valid as they once were.

complexity, large-scale Pacific / North American atmospheric patterns could respond and adjust to global climate change in a variety of ways.

The Effect of Large-scale Oceanic and Atmospheric Circulations on Climate

Two general oscillations of the ocean and atmosphere strongly affect California's climate and weather, and therefore, its habitats and ecosystems: the El Niño / Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) (Wilkinson et al. 2002).

The El Niño is a weakening of the trade winds and warming of the surface layers of the eastern and central Pacific Ocean. This effect occurs on average about every 2 to 7 years, and typically lasts about 6 to 18 months (Cayan 2002). An El Niño is accompanied by swings in the Southern Oscillation (SO), a seesaw of high and low pressure in the southern Pacific Ocean. During the warm tropical Pacific (El Niño) phase of ENSO, the wintertime Aleutian low system tends to expand, so that north Pacific storms are displaced southward and the southern part of the western United States, including Southern California, has increased likelihood of heavy precipitation, whereas, the Pacific Northwest tends to be drier. Northern California is not reliably wet or dry during most El Niño events, although it seems to be wet during very large El Niños. The West Coast, especially the Pacific Northwest, has a greater likelihood of having a mild to warm winter season during El Niños (Cayan 2002).

The PDO is a longer, decadal phenomenon, which features a recurring pattern of ocean-atmosphere climate variability that is centered in the north Pacific Ocean. It can be described as an El Niño-like pattern with a much longer time between the different phases of the oscillation. The PDO events persist for about 20 to 30 years, rather than ENSO's 6 to 18 months (Mantua 2001). The two most recent reversals of the PDO occurred in 1947 and 1977, and there are some indications that it may have reversed itself to a cold phase in the last few years (Mantua, Hare et al. 1997; Hare and Mantua 2000), as show in Figure 2 below.

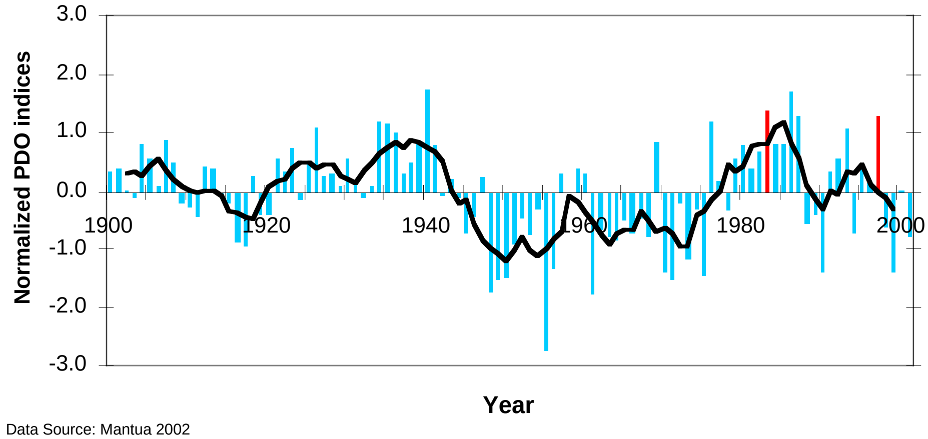


Figure 2. PDO Pattern, 1900–2000

The warm phase of the PDO is characterized by relatively cool sea surface temperatures (SSTs) in the western and central North Pacific, which coincide with unusually warm SSTs close to the west coast of North America (Mantua 2001). Changes of the PDO from one state to another produce widespread ecological changes (Ebbesmeyer 1991), such as the decline in salmon populations in Washington, Oregon, and California that occurred after 1977 (Mantua, Hare et al. 1997) under the warm phase of the PDO. A recent study of tree-ring records in California and Northern Mexico shows a close correlation between these records and the PDO (Biondi, Gershunov et al. 2001). For this reason, the tree-ring records were used as a proxy to estimate changes in the PDO state prior to the historical period—extending the record for a period of about 400 years. The data suggest the conditions in the twentieth century were unusual in comparison with the prior 300 years' data. The differences may be the result of anthropogenic greenhouse warming or just a result of natural variability (ibid.) .

Figure 3 presents the time series of an index (i.e., sea surface temperature at the equator close to the Galapagos Islands) that is used to track the evolution of El Niño events.

It is important to note that in the last 100 years, two of the most intense El Niño events occurred in 1982 and 1997. After 1977, PDO was in its warm phase, which helped amplify these El Niño events (Gershunov and Barnett 1998). Figure 3 also shows that during these two extreme El Niño events the PDO was also in its warm phase, amplifying the severity of these two El Niño events. Some modeling results using global circulation models have

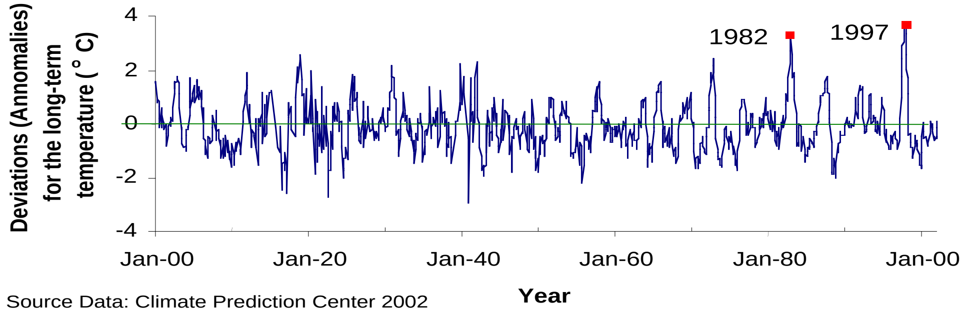


Figure 3. El Niño Anomalies

suggested that climate change will result in more frequent and intense El Niño events (Timmermann 1999, Federov and Philander 2000) but there is still no definitive consensus on this matter (Fedorov and Philander 2000). More frequent and intense El Niño events could have serious implications for California, increasing the number and severity of high-precipitation events with resultant effects on flooding. What is also troublesome is that some scientists believe that global warming may manifest itself in modes of natural climate variability, which may increase the difficulty in detecting the climate change signal (at least at the regional level) (Palmer 1999).

Increased Surface Temperatures

The U.S. National Research Council's (NRC) Committee on the Science of Climate Change confirmed that, "Greenhouse gases are accumulating in Earth's atmosphere as a result of human activities, causing surface air temperatures and subsurface ocean temperatures to rise. Temperatures are, in fact, rising."[8]

Much data has shown that global mean surface air temperatures have risen during the twentieth century. The diurnal temperature profiles, however, have not increased uniformly. On a global scale, daily minimum temperatures are increasing at a faster rate than maximum daily temperatures (Easterling, Horton et al. 1997). In California, a similar trend (i.e., more warming at night and during spring) for the period from 1951 to 1997 was observed for the Napa region. This small increase in temperatures resulted in about a 20-day reduction in frost occurrences and a increase of the growing season length. So far, this change has been beneficial to grape growers, and has increased the quality of the wine produced in this region, but further warming may result in an increase of fungal and vector-borne disease outbreaks (Nemani, White et al. 1999).

As California experiences climate change, some extreme events, like the frequency of heat waves and very heavy precipitation, are expected to increase. Widespread, extended

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[8] National Research Council. 2001. *Climate Change Science: An Analysis of Some Key Questions,* Committee on the Science of Climate Change, Division on Earth and Life Studies, National Academy Press, Washington, D.C. (http://www.nap.edu).

periods of extremely high temperatures (such as unprecedented high nighttime temperatures) are also expected to become more frequent. Higher temperatures lead to higher rates of evaporation and precipitation, so as the Earth warms, there should be more precipitation. It is likely to fall over shorter intervals of time, thereby increasing the frequency of very heavy and extreme precipitation events (IPCC 1996; Easterling, Meehl et al. 2000; Kim 2003).

Changes in the Timing of the Sierra Nevada Runoff

The last three decades have seen a reduction in the portion of the annual runoff that occurs during spring and early summer in high-elevation streams in California (Roos 1990; Dettinger, Ghil, et al. 1995). Also, the timing of the first major snowmelt–runoff pulses has come earlier (Cayan 2001). This shift seems to be correlated with changes in the warm phase of PDO in the late 1970s, but it may also be associated with a potential long-term warming of the landmass in North America. As discussed above, climate change that occurs as the result of increased GHGs in the atmosphere may also be altering the frequency and amplitude of large-scale ocean-atmospheric oscillations such as the PDO and ENSO. For these reasons, it is unclear how much of the observed changes in the timing of the Sierra Nevada runoff is attributable to natural variability and how much is attributable to a warming planet. Changes due to natural variability should reverse themselves at some point; whereas, changes due to global warming would continue in the foreseeable future.

Some models indicate that, on average, 30% of California's increased precipitation will fall in the spring and autumn, with even larger increases in winter. In addition, a greater proportion of the precipitation will fall as rain, decreasing the snowpack in the mountains. Changes modeled for the summer were not statistically significant. (Kim 2001). Timing of precipitation is important, because water systems in California are based on the concept of storing water during the wet season and in wet years and conveying that water long distance to areas of use. A substantial amount of winter precipitation has historically been stored in the snowpack, which melts as the water in reservoirs is used up, recharging them. Less snowpack means less reservoir water is replaced for use in the summer. More extreme spring storms are also likely to fill available winter flood storage space in the reservoirs. Such effects are demonstrated in a recent regional climate study that modeled the effects of a doubling of CO_2 on California climate and found that temperature increased "…everywhere in the region annually (up to 3.8°C), and in every month, with the greatest monthly surface warming at high elevations. Snow accumulation decreased everywhere, and precipitation increased in northern regions by up to 23%, on a mean annual basis." (Snyder, Bell et al. 2002).

Even though scientists concur that California will get warmer; there is no complete agreement on the level of this warming. With respect to climate change's effect on precipitation in California, the situation is also uncertain. The majority of modeling results suggest that California would experience, in general, higher precipitation levels—but there are also modeling results that suggest slightly lower precipitation levels from historical levels (Wigley 2000, Miller 2003). For this reason, in an ongoing PIER-funded project on climate change, researchers are using modeling results that represent the widely divergent potential results with respect to precipitation (i.e., dry and wet scenarios) (Miller 2003).

Sea Level Rise

Sea level has risen in California, as shown in Figure 4. These data are in agreement with reported overall increases at the global level IPCC (IPCC 2001). Sea level rises in response to several factors, such as the thermal expansion of the ocean as it warms, glacier melting, changes in the mass of the polar ice sheets, and land motions. This last factor is attributable to post-glacial rebound and tectonic motions and subsidence from the depletion of underground oil/gas fields and removal of groundwater from aquifers. In California, significant changes of ground level from the widespread pumping of groundwater and oil have been reported for the Los Angeles area (Bawden, Thatcher et al. 2001).

El Niños usually produce heightened sea levels (often by several centimeters above tide predictions) along the California coast. Over a longer time frame, sea levels at California tide gages have been rising by about 15–20 cm (6–8 inches) per century, and most experts expect climate change to cause an additional increase (perhaps double the present rate) to this rise. Because El Niños produce higher sea levels and increase the number of vigorous winter storms, the likelihood of coastal flooding, erosion and structural damage is probably greatest during future large El Niño episodes. (Flick 1984; Bromirski et al. 2003; Douglas 2000).

All the factors that contribute to sea level change make it extremely difficult to estimate the contribution of these factors to the observed sea level changes. Modeled sea level rise in the twentieth century is lower than the observations and there is a continuous scientific debate about the reasons for these differences and the implication with regard to this and the next century (Church 2001).

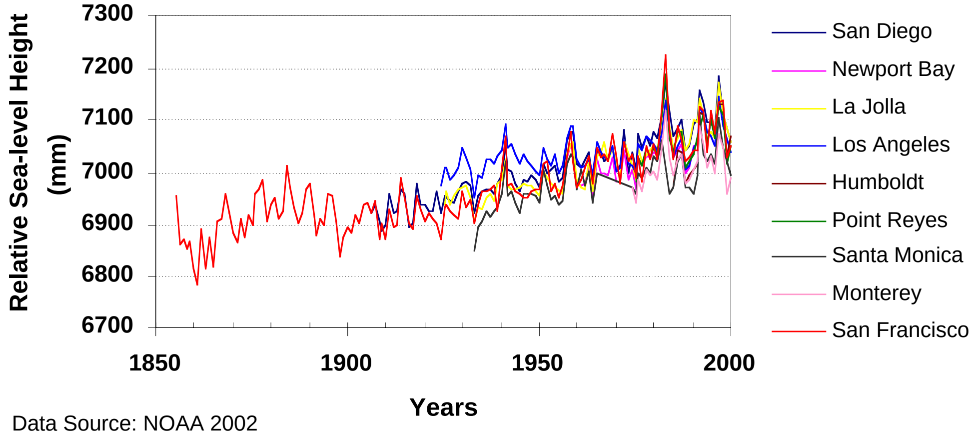
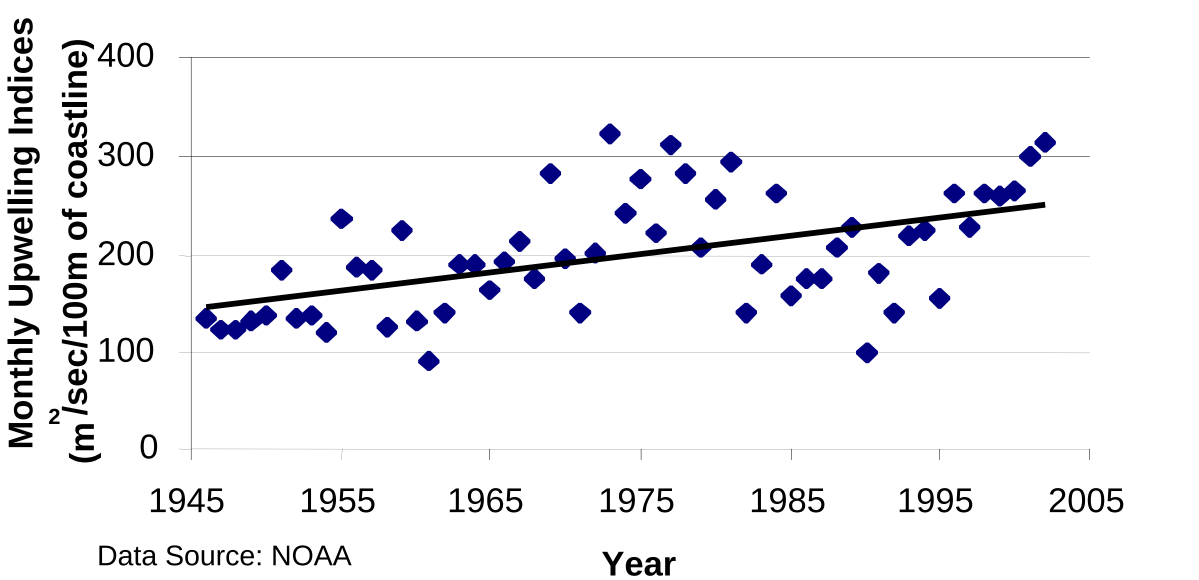


Figure 4. Sea Level Rise on California's Coast

Upwelling

In the summer, winds along the coast of California arrive predominantly from the north. The effect of the wind and the rotation of the Earth result in the movement of surface waters offshore (away from the coast), which in turn results in the vertical transfer (*upwelling*) of relatively deep waters to the surface. Upwelling brings to the surface nutrient-enriched water that supports an abundant ecosystem with valuable commercial value. In 1990, Andrew Bakun postulated that global climate change was intensifying the coastal ocean upwelling in California and in several other locations in the world (Bakun 1990). A more recent analysis for California confirms the increased upwelling along the California coast (Schwing and Mendelssohn 1997). Figure 5 illustrates this upwelling trend. This increase in upwelling, however, has not resulted in a concomitant increase in nutrients, because the region of cold water in the ocean seems to be moving to deeper levels in the ocean. In fact, from 1951 to 1993, surface waters in Southern California warmed by about 1.5°C (2.7°F) (Sanford 2002).

2.3 Potential Impacts of Climate Change in California



timing and levels of precipitation (and the affect of warmer temperatures on the extent and the duration of mountain snowpack) would alter the amount of electricity hydroelectric facilities could generate. It would also affect seasonal availability, with less water available for hydroelectric generation in the spring and summer months, when demand is highest. In addition, there is a high likelihood that dramatically changed precipitation and runoff patterns would lead to changes in broader water policies and end-use priorities, which could further limit hydroelectric production.

Regional climate change is also likely to affect energy demand in California independent of its direct effects on supply, through hydroelectric generation. In projecting these demand-side impacts, account must be taken of patterns of energy use in the state and how they interact with weather conditions. The energy industry uses heating degree-days (HDD) and cooling degree-days (CDD) to estimate energy consumption. Both measure the deviation of the daily average temperatures with respect to a given ideal temperature. In general, scientists assume that energy consumption will increase in direct proportion to the increase of these parameters. For example, a CDD that doubles from one day to another should more or less double the air-conditioning needed for comfort. Figure 6 shows that the long-term 30-year average CDD are increasing in California, at least for the meteorological stations shown in this figure. Peak electricity demand in the state occurs during hot summer days and is associated with increased cooling demand. As demonstrated by California's recent electricity crisis, increases in peak load can dramatically reduce the reliability of the electric power system and result in greatly increased costs to households and businesses. On the other hand, heating degree-days are decreasing, suggesting that less energy may be needed to keep our houses and buildings warm.

An ongoing PIER-sponsored study has estimated tentatively the impacts of higher temperatures on energy expenditures in California, taking account of the effect of higher temperatures in lowering energy consumption for heating houses and buildings. The study has found that this "beneficial" effect does not counterbalance the energy consumption-increasing effects of higher temperatures in the form of higher cooling demand. In addition, and not surprisingly, the difference in impacts would differ

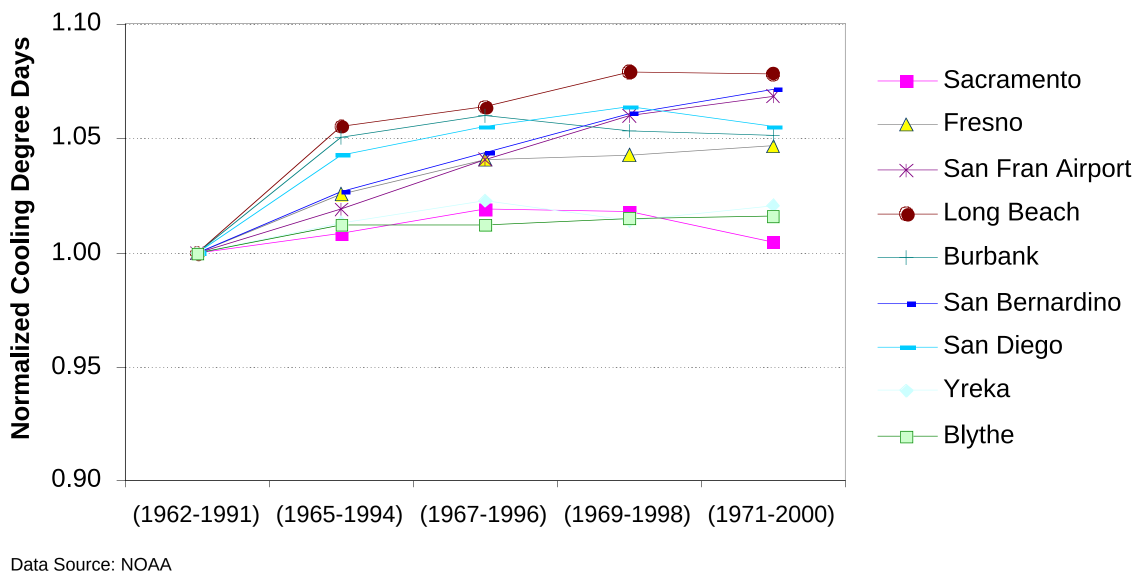


Figure 6. Normalized 30-Year Average Cooling Degree Days

significantly among California's various counties. Energy demand would most likely decrease in the state's northern and mountainous counties; whereas, energy demand in central valley and southern counties would most likely increase. The increased net energy demand (natural gas and electricity) attributable to a warmer climate would be substantial—about 20% over what would be expected under a stable climate (Mendelsohn 2003).

In addition to its role in hydroelectric production, the state's intricate system of reservoirs, canals, aqueducts, and other facilities distributes millions of acre-feet of water around the state annually for use by the residential, commercial, industrial, and agricultural sectors. The performance of this water infrastructure would be directly affected by dramatic changes in temperature and precipitation. California's engineered water systems are already overtaxed, and every major water supply source in California is beyond its physical or legal capacity to be sustained (Wilkinson et al. 2002). Currently, more than half the population depends on water imported from outside their area. Past water management practices and other factors have devastated California's natural aquatic, riparian, and wetland ecosystems, and the challenges posed by climate change and variability will add to the already difficult water problems facing the state. An early 1990s analysis estimated that water-related losses in California due to global climate warming could amount to as much as a billion dollars annually (Vaux 1991).

Threatened Ecosystems

California has a highly diverse landscape that ranges from cool, wet redwood forests in Northern California to hot, dry Mojave and Colorado deserts of Southern California, with many variations in between. As a result, the state hosts more plant and animal species than any other, including 300 natural plant and animal communities, 178 major habitat types (Schoenherr 1992), ten broad biological categories, or "bioregions" based on distinct and consistent climate zones, and 10 floristic provinces that are further divided into 24 sub-provinces (Hickman 1993). There are in the state 5,057 native and nearly 1,000 exotic plant species and almost 1,000 native vertebrate species including 540 birds, 214 mammals, 77 reptiles, 47 amphibians and 83 freshwater fishes (Schoenherr 1992). If one were to include insects and other invertebrates, greater than 50 percent of known species are endemic to California (ibid.).

This rich abundance of flora and fauna is already threatened by forces such as land-use changes, invasive species, and air and water quality degradation. Climate change impacts will intensify those threats through increases in temperature, changes in precipitation levels, increased atmospheric CO_2 concentrations, potential increases in extreme events, runoff, and evaporation—as well as from changing ecosystems, changes in snowpack levels, soil moisture, and sea level rise (USGCRP 2001).

Many ecosystem changes illustrate the interrelationship between California's changing ecosystems and its changing climate. The earlier onset of spring, estimated by changes in the blooming of plants (Cayan 2001), temperature increases in the Sierra Nevada since the

1940s (Dettinger et al. 1995; Karl et al. 1993), the observed increased spring salinity in the San Francisco Estuary (Knowles and Cayan 2002), and the increased intensity of larger floods in the last three to four decades in some of the major Sierra Nevada streams are some of these documented changes (Cayan 2003).

As the climate changes, the impact on California's animals, insects, and vegetation will vary, depending on a variety of factors such as their location and the number and intensity of stress factors present. Impacts could include stronger competition with non-native species; decreased biodiversity; reduced habitat as a result of temperature, fire, or drought; and increased exposure to pests and pathogens.

Several studies already report observed responses of individual or groups of California species to California's climatic changes. For example, from 1951 to 1993, there was an 80% reduction of zooplankton volume in California waters (Roemmich and McGowan 1995). Because zooplankton play an important role in the food chain, the continuation of this decline should have deleterious consequences on marine ecosystems. The increased upwelling (but with a reduced contribution of deep nutrient-rich waters) may explain the observed decline of the zooplankton (Sanford 2002). There is some evidence of the potential reversal of this decline, which may be associated with the speculated reversal of the PDO to its cold phase, as discussed above (Greene 2002, Chavez 2003).

As another example, the population of invertebrates in the intertidal zone at Hopkins Marine Station in Pacific Grove has changed dramatically since 1931. Long-term records of sea surface temperatures at this station show a sustained warming. The record shows that almost all southern species increased in abundance; whereas, most northern species decreased, indicating a migration to the north in response to warmer waters (Sagarin 2002).

Reported geographic range shift in some species are in agreement with the observed climate changes in the state. For example, populations of Edith's Checkerspot butterflies moved north and uphill in accordance with increasing temperatures in their habitat. (Parmesan 1996).

Some potential impacts are being modeled, as well. For example, under funding from PIER, researchers are studying potential robust adaptation strategies for the California coastal sage scrub ecosystem under scenarios of changing regional climate. The coastal sage scrub is home to about 100 potentially threatened or endangered species (NCCP 2002) and constitutes an excellent case study of an ecosystem affected by multiple stresses, such as increased urbanization and a changing climate. A state-of-the-science dynamic vegetation model was used to estimate potential changes in vegetation patterns in California under different climate scenarios. Also, the researchers enhanced an urban expansion model to estimate the potential increase of urbanized areas in the state up to the end of this century. The project identified areas that would "survive" both the increase reduction in habitat due to increased urbanization and would have adequate climatic conditions for survival under all the potential climate change scenarios. Two strong messages arose from this preliminary analysis: (1) urbanization and other stresses should be considered in climate change impacts and adaptation analyses, and (2) improved projections for the regional climate are essential in order to narrow uncertainty and estimate the highest-probability scenarios for climate change in California over the coming decades.

Air Quality

The observed trend towards higher surface temperatures in California may complicate the efforts being undertaken to improve air quality conditions in the state. Preliminary modeling analyses suggest that the Los Angeles region may not be able to comply with the national ozone air quality standards by the end of this decade, because higher temperatures will increase the surface ozone concentrations. The modeling results also suggest, however, that particulate matter concentrations would be lower than expected, because higher temperatures result in less particulated nitrate formation (Kleiman 2002). In the Sacramento region, air quality regulators have also reported a tendency towards more days with meteorological conditions favorable for ozone production (surface temperatures higher than 95˚F and stagnant conditions) (Tollstrup 2002).

Economic Impacts

Understanding and quantifying the potential economic impacts of climate change in California is a major research undertaking, and one of the key elements of the plan presented in Section 3. Nevertheless, it is useful to illustrate potential impacts with examples from the historical record. The economic costs of floods, wildfires and forest fires, and excessive heat or cold are substantial. As shown in Table 1, significant flooding has occurred in recent years in California, resulting in considerable damage to property and crops. Wildfires and forest fires do not occur as frequently as floods, but can result in significant damage—especially to property; the financial loss from crop damage has been relatively less, but is still significant. Excessive heat or cold ("temperature extremes") can result in little property damage, but can lead to significant crop losses and damages—as much as from flooding or wildfires. And extreme temperatures lead to more loss of human life than the other events. As shown in Table 2, fires can be just as costly as the most severe El Niño.

Table 1. Key California Storm Events

Storm Event	Time Period	# Events	Property Damage	Crop Damage	Deaths
Floods	1/1/97–4/30/02	599	$841M	$230M	31
Wild/Forest fire	1/1/90– 4/30/02	264	$845M	$20M	3
Excessive heat or cold	1/1/90–4/30/02	113	$305,000	$846M	46

Source: National Climatic Data Center, Storm Even database: http://www4.ncdc.noaa.gov/cgi-win/wwcgi.dll?wwEvent~Storms

Table 2. Other Major Events in California

Event	Time Period	Damage in California
Oakland / Berkeley Fire[9]	1991	$2 billion in insured losses (at 1997 prices)
El Niño[10]	1982–1983	$2.2 billion
El Niño[11]	1997–1998	$1.1 billion

Sources: See footnotes.

Even temporary disruptions to infrastructure systems can threaten the health and economic security of individuals, communities, and the state. For example, 1998 El Niño-related storms shut down major rail lines and interstate highways, severed communication and power lines, ruptured gas and oil pipelines, overwhelmed sewage systems, and damaged water supply systems. Economic impacts across the United States were estimated to be on the order of $25 billion, and those in California were estimated to be $1.1 billion (NOAA 2002).

2.4 California Greenhouse Gas Emissions

The previous sections have discussed potential impacts of climate change on California. A complementary topic is California's contributions of GHGs to the global atmosphere, which could be subject to mitigation under future national or state policies. By way of background, carbon dioxide, methane, and nitrous oxide are the three primary GHGs produced by human activity. Carbon emissions, the largest contributor to global climate change, are attributed to four major sectors: transportation, industrial and commercial, electric utilities, and residential. The United States is the world's largest producer of GHGs, both in terms of per capita and total emissions. In 2000, the United States released 1.56 billion tons of carbon dioxide into the atmosphere. Nationwide, CO_2 emissions are accelerating. The average annual growth rate is 1.5 percent, but in 2000, the CO_2 emissions rate jumped to 2.7 percent (Shogren 2001).

The California Energy Commission maintains an ongoing effort to measure and document California's GHG emissions. The following section briefly summarizes the main findings of a recent inventory prepared by the Commission.

California's Greenhouse Gas Inventory

[9] Source: Insurance Services Office. 1997. "The Wildland/Urban Fire Hazard." New York, NY.
[10] Source: "The Economic Implications of an El Niño," NOAA Magazine Online (story 24). Web site: www.noaanews.noaa.gov/magazine/stories/mag24.htm
[11] Source: Ibid.

The Energy Commission's *Inventory of California Greenhouse Gas Emissions and Sinks: 1990–1999*, presents the Commission's preliminary GHG emissions and carbon sink[12] estimates for the 1990s (California Energy Commission 2002). The report examines CO_2, methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6), and focuses on anthropogenic emissions (i.e., those attributable to human activities).

Carbon dioxide emissions represent about 85 percent of the GHG emissions in California, and the vast majority of these emissions are generated from the combustion of fossil fuels. Carbon dioxide emissions from the combustion of fossil fuels have remained close to the maximum levels emitted in the mid-1970s, as shown in Figure 7.

There are several factors that explain this phenomenon. Most significantly, California power plants switched almost completely from residual fuel oil to natural gas in the mid-1970s (because of both cost advantages and regulatory restrictions). Other factors that contributed to these nearly static emissions levels include: California's innovative energy efficiency programs, increased penetration of renewable resources for electricity production, increased use of nuclear energy (from about 10,000 GWh per year in 1975 to about 30,000 GWh per year after 1988), increased fuel economy in the transportation sector, and an increase in the amount of imported electricity (California Energy Commission 2002).

[12] Natural processes can act to store GHGs, thereby reducing the total amount of GHGs emitted into the atmosphere. These processes are called *sinks*, and include land-use and forestry activities that can affect the net amount of CO_2 emissions by absorbing and storing carbon through photosynthesis.

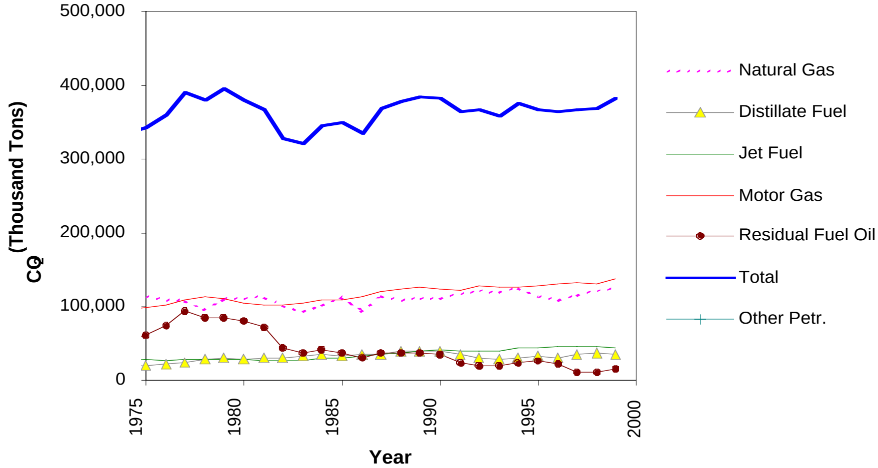


Figure 7. California Carbon Dioxide Emissions, by Fossil Fuel

The effect of energy efficiency programs is clearly shown in Figure 8, which illustrates that California's per capita electricity use has remained practically unchanged, compared to national per capita use, which has increased by approximately 1.5 percent per year.

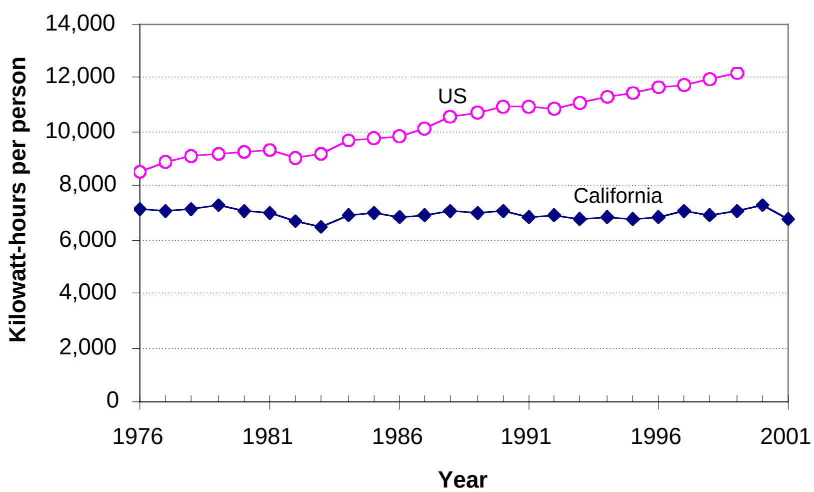


Figure 8. California Per Capita Electricity Use

Figure 9 presents CO_2 emissions from the combustion of fossil fuels per capita and per gross state product (GSP) or gross domestic product (GDP) for California and representative countries. California's emissions per GSP are lower than emissions per GDP for some of the major industrialized countries, but still higher than the emissions from various others, including France, Sweden, and the Netherlands. On a per capita basis, California emissions are higher than nearly all the countries listed, and lower than emissions in the United States as a whole and in Canada. A similar analysis, comparing California emissions with those from other states in the United States, indicates that California's per capita and per GDP CO_2 emissions are among the lowest in the country A milder climate and a less energy-intensive manufacturing base contributes to these lower emissions, but a more energy-efficient and less carbon-intensive economy also contributes to the California's relatively flat emission levels (California Energy Commission 2002).

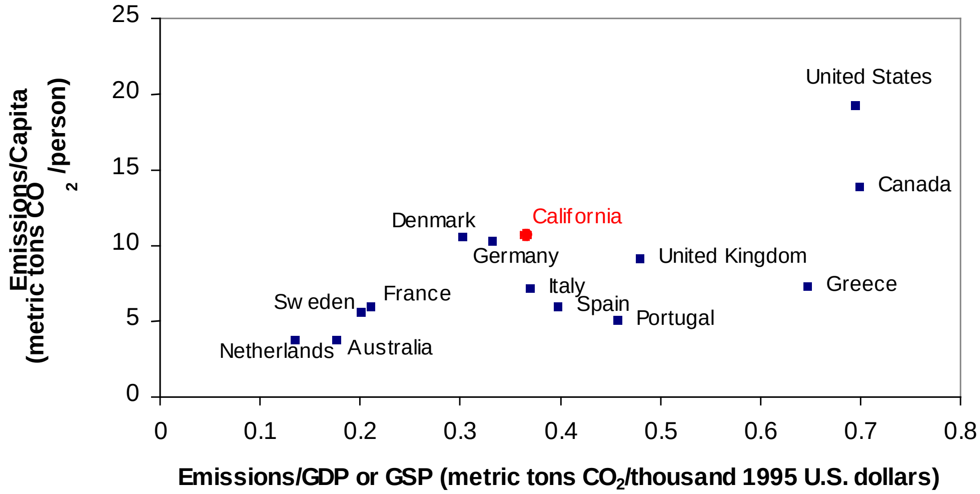


Figure 9. CO_2 Emissions from the Combustion of Fossil Fuels, Per Capita and Per GSP or GDP.

As Figure 10 shows, California's electricity production relies heavily on natural gas, hydroelectric power, and nuclear power. This is in sharp contrast with the United States as whole, which relies heavily on coal to generate electricity.

Power Plants: Major Contributors to GHG Emissions in California

In-state electricity generation contributes about 16% of the annual carbon dioxide (CO_2) emissions (about 55 tons per year) from all the sources located in the state. California's electricity consumption, however, is responsible for much higher emissions, because the state imports a substantial amount of electricity from other states—some of which is generated by coal-burning power plants. Burning coal generates about twice the amount of CO_2 per unit of energy released during combustion than natural gas, the fuel of choice in California. Even though California only imports about 30% of the electricity consumed in the state, out-of-state power plants emit more CO_2 than in-state power plants (California Energy Commission 2002).

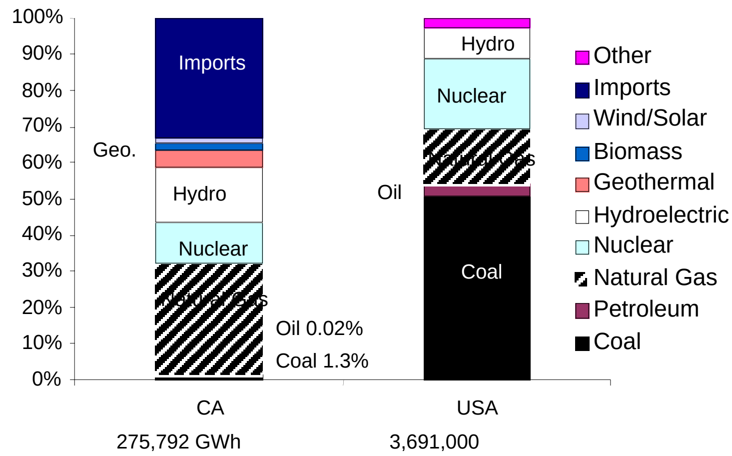


Figure 10. California's Electricity Generation Mix: 1999

2.5 Summary

The climate is changing, both globally and on a regional scale that will directly affect California. The exact details of climate change in California over the coming decades cannot be predicted, but there is a likelihood that current trends will continue or be exacerbated, and that both variability and sudden shifts or "extreme events" may increase. There is a high likelihood of not just further increases in temperature but also alternations in patterns of precipitation, including storms and the timing of rain and snowfall in the Sierras, as well as sea level rises. These various changes will affect energy production and demand, the state's extensive water infrastructure, ecosystems, and air quality.

3. PIEREA Research Agenda and Benefits

The following subsections summarize the PIER climate change research agenda. As discussed in Section 1, this agenda is based on research roadmaps commissioned by PIER, but constitutes a selection of topics in each research area that have been identified as priorities for support with the limited resources available to PIER. These priority topics were chosen according to the following criteria:

- relevance to PIER objectives,
- potential to generate useful results in a four- to five-year time frame,
- potential to inform policy decisions,
- the magnitude of potential impact on the science/art of regional impacts and adaptation analysis,
- ability to generate co-benefits (i.e., a "no regrets" strategy) , and
- potential for securing co-funding.

This research plan is intended to provide a structured California climate change program that can be enhanced and extended with collaboration and funding from other state, federal, and private entities. Potential sources of co-funding include: the National Oceanic and Atmospheric Administration (NOAA), the National Science Foundation (NSF), the National Center for Atmospheric Research (NCAR), the University of California Kearney Foundation of Soil Science, EPRI, the Consortium for Agricultural Soils Mitigation of Greenhouse Gases (CASMGS), and the Consortium for Research on Enhancing Carbon Sequestration in Terrestrial Ecosystems (CSiTE).

Each subsection begins with background information, lists policy-relevant questions, and describes the PIER projects or project areas selected for support. Each subsection also identifies the benefits of the selected research.

Two research areas—*Climate Change Sensing and Modeling* and *The Economics of Climate Change Mitigation and Adaptation in California*—represent this research plan's main core of activities. Improved understanding, and projections, of potential climate changes in California will be primary inputs to all other research activities. Similarly, economic analysis will integrate the PIER- and available non-PIER-funded studies into a common analysis framework, using a language and method of evaluating benefits that can inform policy initiatives.

Within the research agenda of each topic is a critical research path that connects projects that are essential for the development of tools and methods needed to answer the policy relevant scientific questions. Projects will receive either high, medium, or low levels of support from the PIER program. The medium level will consist of PIER funding combined with outside co-funding, and low levels of funding will apply to projects funded mostly with outside funding. In the latter case, PIER would provide mostly seed money to undertake these projects, but vigorously persuade other funding agencies of their importance. In all cases, PIER will try to leverage its resources, to contain costs and maximize benefits to the state.

3.1 Climate Change Sensing and Modeling

Researchers have performed climate change impact analyses for California for more than a decade. How have they projected future climate conditions for California? Are their efforts adequate for impact and adaptation analyses? The following paragraphs will address these questions and suggest why additional work in this area is needed.

The primary tools for projecting the evolution of global climate—including potential anthropogenic changes—are general circulation models (GCMs), which are numerical representations of the basic physical processes of the entire global atmosphere. For studying regional-scale climatic phenomena, however, GCMs have a fundamental limitation: their degree of spatial resolution (i.e., the average size of the grid cells used to represent the Earth's surface) is on the order of 300 Km. Thus, to take an example from California, GCMs cannot resolve important topographic features such as the Sierra Nevada and the Coastal Ranges, as shown in Figure 11.

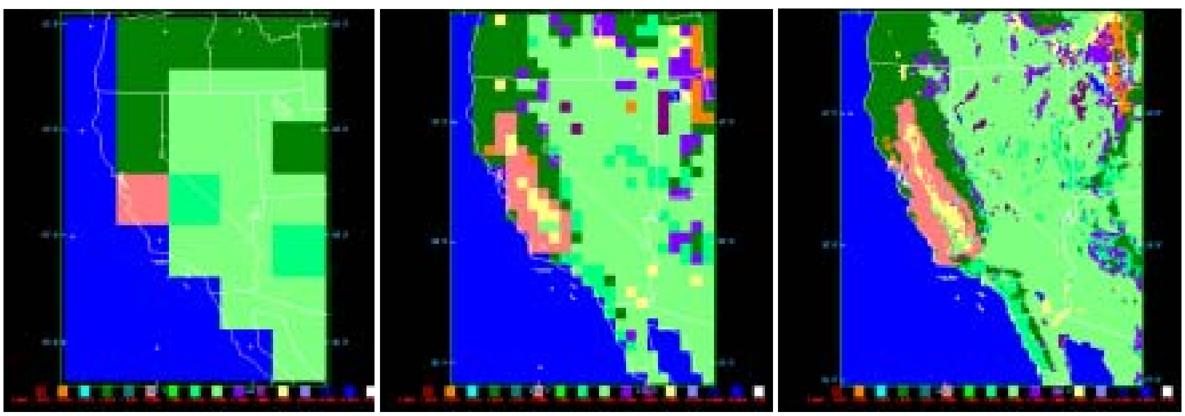


Figure 11. Differences in Resolution Among GCMs. (This graphic illustrates the mountains of California as resolved by various grid-box sizes. The resolution of most GCMs (~300 km) gives no detail of California's mountain ranges. At the 50-km resolution, common to many regional models, the central Valley and Sierra begin to be discernible; whereas, a grid size of 20 km reveals their regional structures, as well as that of the Coast Ranges.)
Source: W. L. Gates. *Modeling Regional Climate Change in California.* 2002.

Impact and adaptation analyses require climatic data at a much higher geographical and temporal resolution than that available from GCMs. Researchers have used several approaches to develop these data. For example, historical California climate data (e.g., the instrumental record of the last 100 years) have been adjusted using factors obtained from GCM outputs to estimate future climatic conditions (Miller 2003). This technique, however, remains subject to the deficiencies of the GCM modeling results at the regional level, because the GCMs do not resolve mountainous features that are important determinants of climate in California. Dynamic or numeric regional climate models (RCMs) suggest that temperatures would increase at a more rapid rate at higher elevations (IPCC 2001, Kim 2001) so this omission is crucial. In addition, it is not clear that the adjustment of historical data by factors developed using GCM modeling outputs result in physically plausible scenarios.

Some researchers have instead used uniform climatic scenarios, which are arbitrarily prescribed constant temperature and precipitation shifts of the historical time series (Mendelsohn 2003, Miller 2003). This approach shares the same drawbacks as the previous method and, in addition, ignores the fact that most of the impacts from climate change may be attributable to increased variability (i.e., changes in weather conditions). Moreover, with this technique there is again a high likelihood that the results will not accurately portray actual physical events.

Climate information at high spatial resolution can also be obtained using dynamic numerical models and/or statistical techniques. The dynamic numerical models (mesoscale models) or regional climate models (RCMs) are similar to the global models, but they are applied to specific regions with grid cells on the order of 10 to 50 Km. The GCMs provide the lateral boundary conditions required by the regional models. Two notable recent examples of this type of work were conducted by Lawrence Berkeley National Laboratory (LBNL) (Miller 2003, Kim 2001) and the University of California at Santa Cruz (Snyder et al. 2002). Their work, however, provides only two or three estimations of potential changes in California climate from a multitude of potential outcomes. Their outputs are heavily dependent on the GCM run used to drive the RCMs. As discussed previously, there are several potential GCM modeling runs that could be used to generate RCM outputs and, in addition, the regional models could be exercised with different initial conditions (ibid.) or with a different range of options and parameters in the RCMs—potentially producing numerous plausible alternative scenarios.

These existing studies also model California's climate under two atmospheric CO_2 concentrations, which represent existing atmospheric CO_2 levels (about 340 parts per million (ppm)) and a doubling of CO_2 concentrations from pre-industrial levels (about 540 ppm). Although this information is very useful, it is now also clear that there is a need to estimate the trajectory of the changing climate with time (transient response), because the response of economic and ecological systems are dependent on how the climate changes with time (Neilson 2002, Schneider 2002).

An alternative to regional modeling is to statistically relate the output of GCM simulations to the climate (or climate-related processes) at specific locations. Such *statistical downscaling* correlates the variability of selected model variables with those observed on a smaller scale, and assumes that this relationship will apply to future climates as well (von Storch 2000). Statistical downscaling has the advantage of being relatively inexpensive to apply.

The users and developers of dynamic models argue that because numerical models mimic the physical processes involved in oceanic and atmospheric phenomena, their use ensures physical consistency among the downscaled variables, as well as between the output from the global models and the downscaled data (Kim 2001). On the other hand, some users of statistical downscaling techniques suggest that dynamic numerical models amplify the known GCM errors and that statistical techniques are preferred because they use the large-scale features that are relatively well-represented by GCM models (von Storch 2000). However, statistical techniques assume that the statistical relationships that are valid under present conditions continue to be valid in the future. This could not be the case for climate change, mainly because the future is highly likely to produce new conditions outside the range for which these relationships were developed (von Storch 2000, Leung 2003). Some scientists consider this caveat so important that they urge "…scientists to use extreme caution before adopting such empirical techniques for global change applications." (Schneider 2002). Statistical techniques may also result in physically implausible scenarios (Kim 2001).

At this time, the best approach to estimate future climate conditions at the regional level is unknown. What is irrefutable is the need for physically plausible scenarios with high temporal and geographical resolution.

Questions That PIER-funded Activities Should Try to Address

Development of climate change scenarios for California, using the best scientific tools, should be a priority for California and for the PIER program in particular. All future impact and mitigation analyses depend on the accuracy of these scenarios. PIER-sponsored research on regional climate should be designed to answer the following questions:

- How is the climate in California changing in relation to the historical and pre-historical conditions? Is this change unique?
- What are the expected signals of a changing climate in the state, and how they should be monitored?
- What are the potential changes of California climatic conditions, based on the increased concentration of GHGs in the atmosphere?
- What is the estimated likelihood of the different climatic scenarios?
- How would the frequency and severity of extreme events change in the future?
- What are the potential impacts from abrupt climate changes in the state and what would the resulting climate look like?

A focused long-term research program is necessary to develop the tools and data needed to answer these questions. The very limited PIER funds will not be able to adequately address all of these questions, but through coordination and involvement with ongoing and new efforts at the national and international levels, we hope to advance the scientific understanding needed to provide meaningful answers to these questions. For example, basic research on abrupt climate change and the development of new GCMs are areas of research that should be in the purview of national and international research institutions. At the same time, however, PIER will encourage the agencies working under the United States Global Climate Research Program (USGCRP) and Climate Change Science Program (USCCSP) to carry out much more high- resolution global circulation modeling, in order to provide more useful input for regional modeling efforts, such as the one to be undertaken in California and to better understand the possibility of more frequent and severe El Niño events, which is one of the potential abrupt changes in climate identified by the National Research Council (NRC 2002).

The research projects described below focus on California. In this subsection, the term r*egional modeling* refers to modeling that encompasses California as a region, but the modeling could include areas of the Western United States, as needed, to produce the information necessary for the California impact/adaptation analyses or necessary to ensure the quality of the modeling for the California region.

PIER Short-term Research Projects

This subsection identifies the project areas to be supported by PIER in the next three to four years. Please note that some efforts—such as the data collection activities—should be permanent and receive PIER support as long as needed.

3.1.1. Compilation and Analysis of Historical Climate and Measurement of Key Variables

A better understanding of a changing climate in California needs a strong observational component and a climate diagnostic effort to make sense of the data and to uncover associations and cause-and-effect relationships between different climatic phenomena. PIEREA will contribute to the development of a long-term climate database for California, using existing data sources and adding key measurement sites as needed. The database will be used to understand how climate has changed and is changing in the state, and for evaluation of regional models.

There are multiple data collections on California meteorological data that have not been included in a comprehensive climatic database for the state. This data includes, for example, fire and agricultural weather observations and data collected during special monitoring programs. PIER will sponsor the development of this comprehensive California-focused climate database. The quality of some of the data will need to be ensured before it is incorporated into the comprehensive climate database. Some of the older data may also need to be digitized.

In some cases, additional monitoring sites should be added. For example, there is a lack of meteorological and hydrological observations in certain remote areas of the state. This data gap is hampering our understanding of some of the important physical processes that have valuable ecological and economic importance, such as the processes involved with high elevation snow accumulation and snowmelt.[13] Numeric hydrological models used to estimate changes in runoff under different climate scenarios have been developed with very limited data from high elevations, and, for this reason, some of processes simulated by these models are ill-known and can only be inferred from indirect measurements. PIER would fund long-term measurements in key locations of parameters such as snow levels, form of precipitation (snow or rain), wind velocity, and temperature designed to gather information that will allow researchers to better understand some of these important physical processes.

For a long time, the absence of measurements in remote ecological sensitive areas has been an issue of concern. The relatively high costs associated with these collecting these measurements (because of their remote locations and the restrictions placed on measurement stations in sensitive wilderness areas) have resulted in very sparse measurement sites in high elevations and other areas. PIER will support the development of new, non-intrusive and less expensive remote monitoring systems to increase substantially the number of monitoring sites and monitoring parameters measured in key regions of the state.

PIER recently initiated a project with Scripps Institution of Oceanography to develop low-cost remote sensing environmental monitors and to install these monitors in Yosemite National Park. Scripps will make the data available to researchers on a near-real-time

[13] http://meteora.ucsd.edu/cap/snow_monitor.html

basis through the Internet. The California Department of Water Resources (DWR) will provide technical support for this project.

In addition, the National Center for Atmospheric Research (NCAR) is planning a reanalysis of climate data that would directly benefit California and could be used to determine which additional monitoring stations should be established to reduce the uncertainties related to estimating changes in climate with a finite number of stations.

The NOAA and the National Science Foundation (NSF) are currently partially funding the development of low-cost remote sensing systems, but more funding is needed to field-test these systems and to install and operate them in key sites in the state. Collaboration with other state agencies is essential for the success of this project.

Benefits: This effort would facilitate better snow-level forecasting and detection of subtle climatic changes, help develop improved models based on higher-quality and more comprehensive data, enhance the state's ability to determine to what extent the observed increase (or decrease) in cooling degree-days (or heating degree-days) is attributable to increased urbanization, and improve understanding of energy consumption patterns and climate.

The development of better climatic databases for the state would result in immediate benefits to the state. For example, the data could be used to develop statistical relationships between snow levels in given years with major climatic indices, such as those used to estimate the strength of PDO and the ENSO events, potentially allowing better forecasting of snow levels, with adequate lead time for planning.

The data could also be used to detect subtle changes in climatic conditions that are not evident when assessing the data from the existing measurement site network. The new data will allow more stringent evaluations of numerical hydrological models, which should result in more advanced and accurate models. Because these models are used for the management of water resources, including hydropower, their improvement should benefit the state even without factoring in climate change benefits.

3.1.2. Intercomparison of Regional Climate Models

Although many regional models have been used to simulate the climate over selected regions of the United States and elsewhere (Houghton et al. 2001), there has been little attempt to evaluate and intercompare the models (i.e., compare the models against each other and against observational data) at the needed resolution. The lack of standardized experimental conditions makes it difficult to identify characteristic model errors. Researchers need to identify a common nested model domain[14] and develop a regional modeling protocol. There is also a need to compare statistical methods against RCMs and historical data not used in the development of the statistical methods.

[14] A model's *domain* is the area being modeled.

Under this project, PIER will fund the development of a modeling protocol to validate and intercompare RCMs and statistical models and other promising modeling approaches. The protocol should provide different alternatives for its implementation and should indicate the levels of funding needed for the options discussed. After the modeling protocol has been developed, the PIER program will decide what option to implement and, if appropriate, proceed directly to the development of climate scenarios based on the results of models already being implemented in California. PIER reserves this option, because even though a modeling intercomparison study would be extremely useful, the high level of resources needed to undertake this effort may preclude this exercise without substantial outside sources of funding.

The intercomparison implementation should use GCMs that have demonstrated modeling results that adequately represent features of interest for California. For example, to the extent feasible, the GCMs should be able to represent the historical variability of ENSO and PDO cycles reasonably well (Collins et al. 2001). Also, researchers should develop or adapt a method from other studies to minimize the influence of poorly performing GCMs when creating ensemble simulations (Giorgi and Mearns 2002).

Benefits: Standardization of modeling protocols would enable the state to evaluate models and compare data, and identify the most appropriate RCM(s) for California applications.

3.1.3. Development of Climate Scenarios for California

The goal of this activity is to help California develop a comprehensive understanding of likely regional climate changes that will affect the State's hydrology and agriculture and natural ecosystems.

If the model intercomparison takes place, the best performing models (both GCMs and RCMs) will be used to develop future climate scenarios for California. If this activity does not take place, selected regional modeling approaches will be evaluated against historical and perhaps paleoclimatic data to ensure an adequate performance of these models and to understand the errors associated with the use of these models. In either case, the models will be used to develop ensembles of regional climate change projections, which will allow researchers to assign probability to the different climate scenarios.

The climate scenario work will be coordinated with the projects on impact and adaptation analyses to ensure that the climate modeling results provide adequate geographical and temporal resolutions for the parameters needed for impact and adaptation analyses.

Recent work by the Pielke Research Group at Colorado State University has shown the importance of considering the effect of anthropogenic land cover changes (e.g., urbanization) and changes in vegetation patterns on global and regional climate (Lu, Pielke Sr. et al. 2001); (Pielke Sr. 2002). Of course, there is a two-way linkage between vegetation patterns and climate (i.e., they each affect the other), which makes these types of studies extremely computationally intensive, but they seem to be essential for producing realistic climate change scenarios. Some researchers are already using GCMs linked to vegetation models. The recent linkage between the Community Climate Model and the Integrated Biosphere Simulator is an example of this work (Delire 2002). At a minimum, the PIER program should explore this issue for the scenario development work.

Benefits: California would gain the ability to develop a comprehensive understanding of likely regional climate changes that will affect its hydrology, agriculture, and natural ecosystems.

3.2 Impacts of Climate Change on California Water Resources

The research roadmap on water resources (Roos 2002) identifies the following priority research items for California:

1. Monitor hydrologically important variables
2. Test operation of the Central Valley Project and State Water Project system with modified runoff
3. Model future precipitation
4. Update depth-duration-frequency rainfall data
5. Evaluate Golden Gate tide datum
6. Catalog sea level trends along the coast, in San Francisco Bay and the Delta
7. Check for recent changes in evapotranspiration
8. Estimate future changes in evapotranspiration and crop use
9. Evaluate effect on major multipurpose flood control reservoirs
10. Model water temperature in major reservoir/river systems
11. Estimate the effect of climate change on regions adjoining California

This is a daunting list of areas of research that cannot be fully supported by the PIER program, because of the limited funds available for climate change research.

The PIER program is currently funding a research project with the University of California at Davis to investigate the impact of climate change on hydropower generation. Hydropower should not be viewed in isolation from the rest of the state water system; therefore, the analysis entails the simultaneous consideration of the effects on agriculture, urban demand, and ecological resources. The researchers, headed by Profs. Lund and Howitt, are using an enhanced version of the CALVIN model for this study. Very preliminary and partial results from this study suggest that groundwater aquifers could ameliorate adverse impacts by acting as new water reservoirs (Zhu et al. 2003).

PIER, together with NOAA and CALFED, is also funding a demonstration project designed to show the benefits of modern hydrological forecasting decision analysis tools. A preliminary study for the Folsom Lake reservoir demonstrated that operational changes at this reservoir could increase hydropower production and free more water for consumption and the environment (Yao and Georgakakos 2001). The same integrated forecast-decision system for Folsom was used to estimate the response of the system under future climate scenarios (ibid.). The study demonstrated that the system could be very effective for coping with the increased variability produced by climate change. The climate scenario analyzed is a relatively wet scenario, and therefore it is unknown if the system would also be able to handle more demanding dry scenarios. However, at least in principle, the new forecasting-decision system should be a significant improvement over the use of existing operational rules. The demonstration area covered by INFORM—a research development, technology transfer, and demonstration program for users of climate information for water resources management—includes the Folsom, Oroville, Shasta, and Trinity reservoirs. This project represents a "no-regrets" strategy that, if successful, will result in better operation of the existing reservoirs in the near future and a more flexible system that would be able to alleviate some of the potentially adverse climate change impacts.

Finally, PIER just started a project with Scripps Institution of Oceanography to develop and install a number of remote sensing devices to measure snow levels and other meteorological and hydrological parameters in Yosemite National Park. The data will be collected in a near-real-time basis, allowing detailed studies of snow-streamflow dynamics that will be extremely useful for future hydrological modeling development and validation work. The long-term operation of these stations may also serve to detect the sign of changing climatic conditions in the state.

Questions That PIER-funded Activities Should Try to Address

Hydroelectric generation is an important resource in California, representing about 20% of the electricity generation in the state. California also imports a significant amount of hydropower from the Pacific Northwest.

- How may climate change and population growth affect California's future water resources, including hydropower production and ecological systems?
- How should the operation of hydropower facilities be improved, so that the state will be able to cope (or benefit, if feasible) under the expected significant changes in precipitation levels and the timing of snowmelt in the Sierra Nevada?
- What hydrological variables should be monitored to improve our understanding of the natural and managed water systems in the state?

PIER Short-term Research Projects

The following is a list of projects designed to address the questions listed above.

3.2.1. Monitoring of Hydrologically Important Variables

Regular, consistent and sustained measurements of hydrologically important variables are essential to track hydrologically important variables and to verify model predictions. Measurements of variables such as precipitation, and other climate data such as snowpack and streamflow should be continued. Measurement should focus on locations where significant change is expected—for example the mountain snow zone. The measurement program should also consider locations where additional measurements could allow the analysis of important processes.

The work on climate sensing and modeling will be used to identify the best locations in the state for these hydrological measurements, with the dual goal of improving our understanding of important processes and being able to detect the climate change signal as soon as possible. The latter goal will require a long-term monitoring program that should be supported by PIER as long as possible, but conclusive results should not be expected during this plan's implementation period (i.e., the next four to five years).

The NOAA and the NSF are currently partially funding the development of low-cost remote sensing systems, but more funding is needed to field-test these systems and to install and operate them in key sites in the state. Collaboration with other state agencies is essential for the success of this project.

Benefits: This work would result in an improved understanding of important hydrological processes and enable researchers to detect and interpret climate change signals as early as possible. (The latter goal would require a long-term monitoring program that should be supported by PIEREA, but conclusive results should not be expected during the implementation period of this plan.)

3.2.2. Testing the Operation of the State Water System under Different Plausible Climate Scenarios

This work will entail a study of the state water system, with an emphasis on the operation of the Central Valley Project and the State Water Project. These two major water projects furnish about 30% of California net water demand for agricultural and urban uses. The major reservoirs of these two projects are located on watersheds likely to see large shifts in runoff patterns as a result of rising snow levels (i.e., the Trinity, Sacramento, Feather, and American). At least 50 years of monthly hydrology are suggested as a minimum duration for comparisons. Currently, many studies are conducted based on data from the 1922–1994 historical period of 72 years. This longer period includes simulation during the two major six-year historical droughts (1928–1934 and 1987–1992). This work could involve enhancing the CALSIM and CALVIN models. CALSIM is the model developed by the California Department of Water Resources and used for planning purposes in the state. CALVIN is an economic-engineering optimization model of California's water supply system that identifies optimum operation conditions. It is a new model, developed under NSF. As indicated previously, PIER is funding the modification of this model for climate change studies. However, to estimate the likelihood of the idealized optimization results provided by CALVIN, a simulation model like CALSIM may be needed. These models would be used to study the impact of climate change on the availability of water for agricultural, urban, industrial, recreational, and environmental purposes.

At this time, the INFORM project does not include the testing of the integrated forecast-decision system under different climate scenarios that will be developed under the work outlined in Section 3.1. The current phase of the INFORM project will most likely end in 2006. The PIER program should support the testing of the system developed by the INFORM project to investigate the advantages of using this reservoir operation management tool under different climate scenarios.

<u>Benefits</u>: The state would have the ability to study the impact of climate change on the availability of water for agricultural, urban, industrial, recreational, and environmental purposes; and conduct scenario studies of a large portion of its water system.

3.3 Impacts of Climate Change on Ecological Resources

The roadmap of research on climate change impacts on ecological resources identified the following important project areas for California:

1. Ecological assessment and monitoring using ecological indicators specific for climate change studies
2. Development of climate scenarios at adequate resolution for ecological studies
3. Enhancement and development of modeling tools to estimate future changes in vegetation patterns and ecosystems in general
4. Compilation and analyses of paleontological data to better understand past ecological responses to climate change and to test models
5. Development of an experimental and modeling research program to understand the impact of multiple stresses such as impacts form non-native species, air pollution, urbanization, and climate change
6. Evaluation of methods for incorporating climate change concerns in land use and conservation planning.

PIER is currently funding a research program designed to estimate potential changes in vegetation patterns in the state attributable to a changing climate. This study is being conducted with a state-of-the-science dynamic vegetation model (i.e., a model that estimates changes in vegetation patterns as a function of time) called MC1, which combines the MAPPS and CENTURY models (Neilson 2002). In addition, under PIER funding, a group of researchers from the University of California at Berkeley are developing plausible scenarios of urban development in the state. Both studies are being used to estimate the joint impact of climate change and urban development on a particular ecosystem (coastal sage scrub). This study represents a significant improvement from previous studies but, as discussed below, it still did not address some important issues.

Questions That PIER-funded Activities Should Try to Address

As indicated in previous sections, it is now clear that land use changes and vegetation patterns in particular may have a strong effect on regional climate and the hydrological cycle both at the global and regional levels. Of course, climate also affects vegetation patterns; therefore, they form a complex interacting system. Changes in vegetation patterns and hydrology will, in turn, impact energy demand and the availability of hydropower. For these reasons, PIER-supported projects should be designed to address the following questions:

- What are the potential changes in vegetation patterns in California, and how would they affect and be affected by the state's climate and the hydrological cycle?
- How would urban development and climate change affect vegetation patterns in California? Would urban areas impede the migration of species, and therefore be a dominant feature determining vegetation patterns?

PIER Short-term Research Projects

The following is a list of the projects selected to address the above questions. As with all the roadmaps, the selected projects represent a small universe of the potential projects that should be funded to fully address the potential impacts of climate change in the state.

3.3.1. Enhancement and Application of Dynamic Vegetation Models (DVMs) for California

It will not be possible to assess the full extent of ecosystem responses to global climate change through experimentation alone (Aber et al. 2001). To explore ecosystem responses to multiple global changes, researchers will also need to use ecosystem models that utilize critical information from field experiments.

The PIER-funded project briefly described above greatly enhanced our understanding of potential changes in vegetation patterns in California (Lenihan et al. 2003). For example, the DVM that was used (the *MC1*) simulated vegetation succession at large spatial scales through time while estimating variability in the carbon budget and responses to episodic events such as drought and fire. Although these model simulations should not be viewed as predictions of the future, they give important indications about trends that may be important in California as the climate changes. For example, the model calculates that rising temperatures will cause a shift from conifer-dominated forest to mixed conifer and evergreen hardwood forests in northern California.

However, there are still crucial drivers of ecosystem dynamics that are not adequately addressed by the DVMs. Four of these drivers deserve immediate attention:

1. **Land use.** The existing models do not address the impact of current land use, land use change, land cover fragmentation, and the history of land management on ecosystem dynamics. These elements are critical for understanding ecosystem structure and function in a changing world. It is necessary to know the trajectory of land use change for the model to produce a realistic vegetation age structure. Future land use will be a function of both human population growth and vegetation change. In addition, it will be important to understand the distribution of the physical barriers to species

migration that may be imposed by land use change. The role of migration corridors should also be investigated.

2. **Age structure of vegetation.** In the current DVMs, spatially variable age structure of the vegetation is simulated by the model. Although there are efforts underway to compare constructed vegetation age structure with observed age structure, it is unknown how well the simulations replicate observed patterns. Because initial age structure of the vegetation is important for understanding the trajectory of ecosystem structure, it will be advantageous to the success of future model predictions to accurately portray observed age structure at the onset of the model run.
3. **Dispersal rates and modes.** Dispersal rates and modes of different species are not considered in the DVMs. The models need to incorporate the varying dispersal abilities of species in California to adequately assess the impact of a changing climate on community composition of California's ecosystems. Most likely, the inclusion of such information for all species would be cost-prohibitive, but it is essential that the models be able to incorporate information from a few key target species into the model runs with the goal of understanding species-level responses to future threats.
4. **Invasive species.** The DVMs are not currently considering the impact of non-native, invasive species. The introduction and spread of invasive species can cause disruption in an ecosystem's successional trajectory. Non-native species pre-adapted to disturbance could easily colonize altered sites before native species become established. Non-native species can alter disturbance regimes so that further establishment by native species is highly unlikely. For example, the spread of *Bromus tectorum*, a non-native invasive grass to western shrublands, alters the frequency of fires, which in turn suppresses the establishment of native shrubs. Mechanisms involving invasive species, therefore, have a tremendous potential for altering ecosystem structure. Any progress made toward incorporating species-specific dispersal traits from activity 3 above will aid this effort as well. The impact of introduced pest pathogens that cause such diseases as Sudden Oak Death should also be considered for incorporation into the new generation of models.

Dynamic Vegetation Models should also be enhanced to consider the impact of other stressors such as air pollution. These DVMs or reduced form models (i.e., simple models that mimic the behavior of more complex models) should be used with regional climate models to investigate the interaction between climate and vegetation.

This work should be heavily coordinated with field studies to incorporate new findings in the formulation of dynamic vegetation models. The PIER program may also consider providing some seed funds for field studies with a high potential of delivering key insights for DVM improvement .

<u>Benefits</u>: DVMs that model interactions between a greater number of critical ecosystem factors would improve understanding of the impacts of each factor and of the interrelated systems. These models could also enable researchers to identify and interpret ecological trends more readily.

3.4 Carbon Sequestration in Terrestrial Ecosystems and Geological Formations

Terrestrial ecosystems offer significant potential to capture and store carbon at modest costs, providing net social benefits. Recognizing the importance of carbon sequestration in combating global climate change, the Kyoto Protocol to the United Nations Framework Convention on Climate Change (UNFCCC) established the principle that carbon sequestration can be used by participating nations to meet their respective net emission reduction targets for CO_2 and other GHGs (UNFCCC 1997). In September 2002, California's governor signed into law Senate Bill 812, which requires the California Climate Action Registry to allow the registration of carbon reductions produced by the sequestration of carbon in forested lands or by reforestation.

About 31% of California is covered by forest ecosystems (Horwath et al. 2001), with much of this forestland in federal, state, and urban parklands. Most California forests can provide excellent long-term carbon storage in long-growing, woody species (i.e., for thousands of years, barring natural disasters). Changes in management of existing forested lands can increase the amount of carbon per unit of area, and restoration of trees in riparian areas offer another good opportunity. However, forest loss appears to be growing exponentially in California, where more forest land was lost between 1982 and 1997 than during the previous thirty years (Best and Wayburn 2001). In fact, the U.S. Forest Service expects the greatest loss in the next 50 years to come from the Pacific Region: Close to 20% (12 million acres) of non-industrial forest land is expected to be lost to development in California during this time (ibid.).

The agricultural sector in the state also provides excellent opportunities for carbon sequestration. This sector represents over 11% of California's land base. Plant biomass can be returned to the soil in the form of residue, different crops or varieties of crops can be selected to enhance residue production, cover crops can be grown specifically to produce organic material for the soil, and buffer strips surrounding agricultural fields can be managed for carbon sequestration.

Because the large majority of California cropland has been in production for several decades, the large initial release of carbon has already occurred and current releases are now very low (estimates range between 2.7 and 15 million metric tons of carbon annually) (Gephart et al. 1994; Lal et al. 1998). Thus, simply reducing practices that lead to carbon losses would increase carbon storage in soils. California's agricultural soils show additional promise for sequestration, because many are managed year round, which increases their value and the efficacy of using them as a carbon sequestration tool.

Bioenergy—energy derived from biomass—may be produced from purpose-grown crops or forests, from urban carbon-based residuals, or as a byproduct of forestry, sawmilling, and agriculture. Sustainable bioenergy generation results in substantial net reduction of GHGs because the carbon released during combustion is reabsorbed during the next growing season. Biomass can be utilized directly for heat energy or converted into gas or electricity for energy production (especially, small modular biomass systems, sized from 5 kW to 5 MW).[15] California's biomass resource is much larger than what is currently being used. Total biomass in wastes and residues exceed 56 million bone dry tons (BDT) per year—ten times the current use to date (Springsteen 2000). Of this, 16 million BDT can be considered available, with a much larger fraction available if forest fuels reduction programs and energy crops production were to be developed in California (ibid.). Bioenergy may be also one of the best options available to comply with a state law passed in September 2002 requiring that 20% of the electricity sold by electric utilities be from renewable sources of energy by 2017. [16]

Geologic sequestration is a form of direct sequestration, where CO_2 is captured from large point sources of anthropogenic emissions, transported, and injected into underground formations. Some of these underground formations have structure, seals, porosity, and other geologic properties that make them ideal for long-term storage of CO_2. Geologic formations are likely to be the first large-scale option to be considered for CO_2 storage, since developers of geologic storage technologies can draw on the experience gained from oil, gas, coal, and water-resource management (USDOE 2002a). For example, the petroleum industry is currently injecting 30 million tons of CO_2 per year into geologic formations for improving oil recovery (USDOE 2002b).

A study of geologic sequestration options for California suggests that oil reservoirs, gas fields (in the near term), and brine formations (in the long term) present the most promising geologic reservoirs for carbon in the state (Benson 2000). The sequestration of carbon in California oil fields may be an especially attractive option if it is implemented with enhanced oil recovery.

The roadmap of research on carbon sequestration identified the following priority research areas:

1. Improve the understanding of processes and mechanisms involved in carbon sequestration in terrestrial ecosystems and geologic formations in California
2. Identify and assess the technical feasibility and carbon impacts of carbon sequestration practices in California
3. Evaluate the economics of implementing carbon sequestration strategies in California
4. Evaluate the environmental and social impacts of implementing carbon sequestration strategies in California

In addition, the roadmap identified the need to develop guidelines for the design, implementation, monitoring, evaluation, reporting, verification, and certification of carbon sequestration projects in the state and the desirability to coordinate research projects with the creation of the California Carbon Sequestration Network.

[15] Biomass can also be used for fuels (ethanol and renewable diesel) for transportation purposes and in the manufacture of chemicals.

[16] This law does not include large hydroelectric facilities in its definition of "renewable" sources of energy.

The PIER program and CDF are already funding a research project designed to identify, in relatively broad terms, the opportunities for carbon sequestration in existing forested areas or by reforestation in marginal lands at the state level. The researchers are making use of the extensive databases developed by CDF regarding the characteristics and extent of forests and other land types in the state. This project also includes a measurement component for two types of sequestration opportunities (i.e., forestation in marginal agricultural lands and lengthening rotation in existing commercial forests) to be selected by PIER and CDF. That part of the project will test and demonstrate the use of remote sensing instrumentation for verification of carbon sequestration projects. The researchers will also develop monitoring protocols for the two types of sequestration opportunities selected by PIER and CDF.

Traditionally, the electricity-generating sector has been one of the first targeted for mandated emission reductions. The U.S. Congress has already considered a requirement to limit CO_2 emissions from this sector. These proposals also seem to suggest that any emission reduction requirements would allow for a flexible compliance mechanism, as was done for the Acid Rain Program (that is, power plants would be able to reduce emissions from other sources in lieu of more expensive reductions at their own facilities). Therefore, it seems prudent to start cataloging any potentially low-cost options that California electricity ratepayers may use to ameliorate or negate potential adverse economic impacts from potential requirements to reduce CO_2 emissions from in- and out-of-state power plants serving California.

Questions That PIER-funded Activities Should Try to Address

The selection of specific projects for support from the PIER program should be designed to address the following questions listed below:

- What would be the costs associated with carbon sequestration projects in the state? How much carbon would they be able to sequester? What areas are the best sites for these projects?
- What are the potential social, economical, and environmental impacts associated with the most promising carbon sequestration options in the state?
- What would be the role of bioenergy in any efforts designed to reduce GHG emissions from in-state sources?

PIER Short-term Research Projects

PIER has decided not to fund basic research projects on terrestrial carbon sequestration, because these projects are being funded by other agencies and because the limited PIER funds would not be able to make a difference. Instead, PIER will fund applied research projects to generate the information that is needed to inform policy implementation or formulation. With respect to carbon sequestration in geological formations, PIER is willing to provide seed funds to execute the project described in section 3.4.3, but most of the funds must come from other sources, due to the high costs that would be associated with this project.

3.4.1. Development of Carbon Supply Curves for Forestry and Agricultural Soil Strategies in California

Supply curves are graphs or tables showing the cost and amount associated with different sequestration options. The development of supply curves must include analyses of the potential secondary benefits and drawbacks. For example, trees placed in a riparian area between an agricultural area and a stream could help reduce the amount of pollutants from runoff that enter the stream—an added benefit. Conversely, some research has suggested that increasing carbon in soil can also increase the levels of nitrous oxide—a disbenefit.

The development of supply curves for forestry strategies in California would enhance the ongoing PIER/CDF project discussed above by adding more field measurement studies and performing a detailed analysis for one or two California counties. The studies at the county level will allow a more refined analysis, generating more precise cost estimates and more realistic carbon sequestration potential estimates.

In addition, PIER believes that there is a significant potential to sequester large amounts of carbon in agricultural soils at reasonable costs and with great social benefits. Significant field and analytical studies are being conducted outside California with support from the federal government. It is surprising that these large federally funded studies are not supporting research in California, given the importance of California's agriculture. The research on agricultural soil carbon sequestration will involve the following steps:

1. A broad scale study of the opportunities of carbon sequestration in agricultural soils in the state
2. The selection of one or two counties for detailed study
3. Detailed field studies of different promising management practices, as needed
4. An evaluation of existing models of carbon and nitrogen budgets and carbon sequestration (such as the CENTURY model) using the field data collected in the previous phase of the project and model improvement work if the model does not perform satisfactorily
5. An estimation of the costs and carbon sequestration opportunities for the selected county(ies) based on a validated model

Benefits: An economic assessment of forestry and agricultural soil carbon sequestration strategies would help decision makers prioritize those strategies, and also help agricultural and forestry specialists who are involved in allocating resources among competing alternatives. This research would also provide an economic assessment of promising forestry and agricultural soil carbon sequestration strategies. Even without considering climate change benefits, this assessment should be helpful for agricultural and forestry specialists involved in allocating resources among competing alternatives.

3.4.2. Economic Studies of Bioenergy Strategies in California

The PIER program and others are funding research designed to develop or improve technologies that use renewable sources of energy. Under this research plan, PIEREA would complement this work with analytical studies designed to identify obstacles in the deployment of these technologies and proposing solutions. The main goal is to develop an adequate understanding of the private and social costs associated with the use of bioenergy projects as a tool to reduce GHG emissions in California.

Some of the activities that may be undertaken include: (1) collect and analyze costs to farmers and foresters on energy crop cultivation in California (including collection, processing, and distribution costs that will be necessary for large-scale biomass utilization); (2) conduct life-cycle assessment of bioenergy strategies in California;[17] (3) study the economics of biorefineries, to reduce the costs of biomass collection and transport in California; (4) conduct a study of the economic feasibility of using urban carbon-based residuals for bioenergy production; (5) develop models of broad-scale biobased products and bioenergy market development, identifying the impacts of different economic scenarios and the most effective drivers and incentives within each scenario; and (6) develop models of rural development to support production, processing, and utilization of biomass.

Benefits: This project will help develop a more comprehensive understanding of the feasibility and economic factors involved in bioenergy use in California, as well as potential solutions for overcoming barriers to the use of bioenergy in the state.

3.4.3. Carbon Sequestration in Geological Formations

PIEREA proposes to support research designed to address the major technical issues associated with geologic storage in California. Research topics include:

1. Monitoring and verification
2. Risk assessment, human health and environmental impact
3. Tectonic stability
4. Economic analysis / viability of technologies
5. Leakage assessment, petroleum reservoir analogues
6. Performance assessment
7. Evaluation of novel technologies

[17] This work will be coordinated with other lifecycle analyses identified in the PIER Environmental Area Research Plan. Lifecycle assessments for other carbon sequestration strategies might be conducted.

PIEREA will not fund carbon separation technologies (separation of carbon or carbon dioxide from other combustion gases prior to injection) because other entities, including the programmatic PIER areas, are funding those technologies.

PIEREA also proposes to support the development and demonstration of storage technologies through field demonstrations. These will be collaborative efforts between research groups and industrial partners. Candidate technology demonstrations include: 1) Enhanced oil recovery, either miscible or immiscible, optimized for CO_2 storage; 2) Enhanced gas recovery, optimized for CO_2 storage: 3) Disposal in deep saline formations; and 4) Disposal accompanying subsidence mitigation.

Prior to, and parallel to, these technology demonstrations will be a site-selection study to rank potential storage sites in California.

A second parallel activity will address CO_2 sources and storage infrastructures. Present and potential future CO_2 sources need to be characterized. Compression, pipeline, and injection well infrastructure needs to be assessed.

Benefits: The identification and quantification of the feasibility, economics, and potential of various strategies for sequestering carbon in geological formations would help decision makers prioritize options. Implementation of this carbon sequestration option could result in enhanced recovery of oil and gas from California oil/gas fields.

3.5 Inventory Methods and Supply Curves

Inventory Methods

The uncertainties in GHG emissions inventories are relatively high, and that uncertainty may make it impossible to track emissions trends accurately (Rypdal and Winiwarter 2001). Carbon dioxide emissions from the combustion of fossil fuels can be estimated with sufficient accuracy and precision if the energy flows for the inventory region are known. However, this is not the case for non-CO_2 gases. There are significant uncertainties associated with most of the emission estimates for non-CO_2 gases; primarily because the complex factors affecting non-CO_2 emissions are not taken into account by the relatively simple methods adopted by the Intergovernmental Panel on Climate Change (IPCC) and the U.S. Environmental Protection Agency (USEPA). Research needs to identify the limitations of these inventory methods and develop methods that account for the complex factors that affect non-CO_2 emissions.

Supply Curves

Supply curves have been used in a number of disciplines for many years as a way to graphically display, in simple terms, the cost and availability of a resource or other market good. The supply curve paradigm was adopted to characterize the potential costs and benefits of energy conservation in the early 1980s. These early conservation supply curves were intended to graphically illustrate the amount of energy *savings* that could be achieved through widespread implementation of energy conservation measures, as well as the *costs* of achieving those savings. In this way, conservation supply curves were designed to allow direct comparison of the costs of saving a unit of energy with the costs of producing it. Generally, the vertical axis of the curve represents the cost of each conservation measure (usually in dollars per unit of energy saved), and the horizontal axis represents the total amount of energy savings available. Measures are ordered on a marginal, least-cost basis as shown in Figure 12 below.

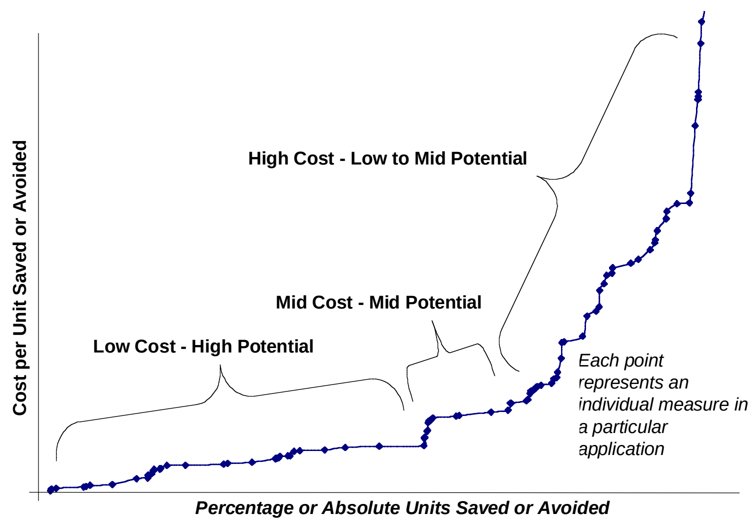


Figure 12. Example Conservation Supply Curve

Over the last ten years, the energy conservation supply curve framework was adapted and applied to the cost and benefit characterization of various GHG mitigation strategies. In these GHG mitigation supply curves, costs are generally expressed in dollars per ton-of-carbon-equivalent reduction and plotted against the total amount of carbon-equivalent reduction that can be achieved by implementing the mitigation measures.

The accuracy of estimated GHG emissions is obviously one of the most important factors in determining the technical integrity of the supply curves. For example, if methane emissions from landfills are overestimated, the estimated cost of controls (expressed in dollars per ton) may give a false impression that the control of those emissions may produce significant environmental benefits at a relatively low cost, or at a net benefit. The development of sound GHG-reduction policies are linked to high-quality emissions data.

If the Kyoto Protocol goes into effect, a formal international carbon market will be developed in the near future. It is unclear, however, how emission reductions in California could be part of this formal international market without the ratification of the Kyoto Protocol by the U.S. government. A national market could be developed as part of the voluntary programs being implemented by various states (including California) and by the U.S. government. These programs allow companies to voluntarily register their GHG emissions reductions, so that they may be considered for potential mandatory emission reduction requirements in the future. The goal is to protect companies that are reducing emissions now by acknowledging their current level of emissions reductions and taking them into account, should a cap and trade (or similar) program be instituted in the future.

An international or national market for GHGs has the potential drawback of funneling significant resources out of California to pay for emission reductions occurring outside the state. Several studies suggest that it may be more economical to reduce emissions in the former Soviet Union or in developing countries instead of implementing "costly" local emission reductions in developed countries. These studies, however, may be misleading, because they do not consider the potential co-benefits of reducing local or national emissions. Although potentially it could be less expensive for an individual company to reduce emissions outside of the United States, such an action does not account for the indirect costs and benefits that make up the net social cost for California and its citizens. For example, reducing GHG emissions in California may also reduce conventional air pollutant emissions and result in substantial air quality benefits.

As discussed in subsection 3.4, power plants in California may at one point be required to offset their GHG emissions. To reduce the cost impact of implementing these potential requirements on electricity ratepayers, it is necessary to catalog the state's available GHG reduction opportunities, to identify the most feasible, cost-effective options.

Questions that PIER-funded Activities Should Try to Address

- What are the costs associated with reducing emission in other sectors of the economy, in comparison to those of reducing emissions from the electricity sector?
- What emission estimation methods should be improved to better characterize emissions and emission reduction opportunities?
- What methodological features should be enhanced to improve the usefulness of supply curves for policy analyses and for their consideration in macroeconomic analyses?

PIER Short-term Research Projects

The following is a list of projects designed to address the questions listed above.

3.5.1. Energy Balances for California

Carbon dioxide emissions from the combustion of fossil fuels are one of the best-quantified emissions. State and federal agencies track the consumption of major fuels such as natural gas, motor gasoline, and diesel fuel relatively well, and emissions can be estimated from that data. However, only federal agencies estimate the consumption of minor fuel such as kerosene, petroleum coke, residual fuel oil, distillate fuel oil, propane, still gas, and other fuels. These "minor" fuels have been shown to be extremely important in the determination of the CO_2 emission trends in California (California Energy Commission 2002).

Every year, the Energy Information Administration (EIA) publishes the *State Energy Data Report,* which contains energy consumption data for every state in the Union. All state-level inventories of GHG emissions are mostly based on this publication. The EIA data is extremely well documented and available in electronic form. The EIA is the repository of fuel sales data, which is provided by organizations engaged in the trade and sale of fuels in compliance with federal law. The EIA also maintains an excellent database of fuel production, storage, and transactions for Petroleum Administration for Defense districts (PADD) in the United States. California is in PADD 5, along with Alaska, Arizona, Hawaii, Nevada, Oregon, and Washington. The EIA uses the fuel sales and PADD data to estimate fuel consumption at the state level, ensuring that all the energy flows are accounted for and add up to the reported energy balance totals for each PADD. The end results are balanced energy flows for every PADD in the nation. An energy flow balance at the PADD level, however, does not guarantee an energy balance at the state level, and it could result in incorrect fuel consumption level data at the state level.

Estimations of California emissions from crude oil refinement could be inaccurate, as well. The amount of crude oil processed in California's refineries decreased since 1990, as shown in Figure 13. Crude oil delivered to the refineries in 1999 was about 636,198 thousand barrels, which represents a 8.6% reduction from the 696,410 thousand barrels processed by state refineries in 1990. The amount of carbon dioxide associated with this reduction is about 26 million metric tons. This amount is very significant, representing about 7% of the CO_2 emissions from fuel combustion in 1990. Although California refineries have increased their productivity since 1990 (Berman and Bui 2001), it is unlikely that this productivity increase could fully explain the significant decrease in the amount of crude oil processed by state refineries, particularly while they are satisfying an increased demand for motor gasoline and other products. Some increase in the amount of imported refined products must have taken place. A significant amount of energy and CO_2 emissions are associated with crude oil refining and, therefore, the import of refined products may have also contributed to the estimated trend of emissions for in-state sources. Only a carefully designed energy balance study for California can determine the role of imports into the estimate emission trends since 1990.

Annual energy consumption and CO_2 emissions from the combustion of fossil fuels in California respond to multiple factors, such as: weather conditions, availability of hydropower, state of the economy, structural changes of the state economy, changes in

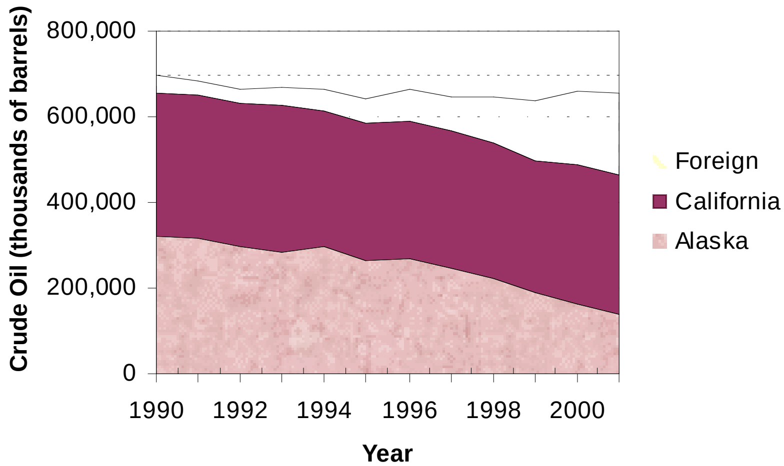


Figure 13. Crude Oil Processed in California Refineries, 1990–2001

energy standards, and regulatory requirements. It has proven very difficult to disentangle the reasons for observed changes in emissions, because there is a lack of readily available disaggregated data that would allow the factors contributing to the observed trends to be analyzed. The pioneering work that sought to understand observed energy consumption trends in California was hampered by the lack of adequate state energy balances (Schipper and McMahon 1995).

Since the restructuring of the electricity system in California, the distinction between electric utilities and non-utilities no longer makes sense. However, the energy consumption data from non-utilities is not readily available and has not been completely subjected to the same quality control procedures that utilities face, which makes data comparisons difficult. The energy balance for California will review the existing fuel consumption data for power plants in the state, regardless of their prior classification as utility or non-utility generators.

In summary, under this research area, PIEREA will fund the development of energy balances for California at the highest possible level of spatial and temporal disaggregation. This work will help researchers improve energy consumption data for California, associated CO_2 emissions data, and the analyses of energy and emission trends. The data will be also used in the economic analyses described in subsection 3.6.

Benefits: Accurate data would be available in a form that researchers can use to improve estimates of energy consumption and CO_2 emissions from the combustion of fossil fuels in California, and more data would be available for economic analyses.

3.5.2. Research on New, Improved Methods to Estimate Non-CO_2 Emissions

Some researchers have attempted to determine the level of uncertainty in the existing inventories by assigning probability to the range of potential parameters affecting emissions. In theory, this approach should work, assuming that the subjective probability distributions are close to reality. The main problem with this approach is that in some cases, the basic equations or methods used to estimate emissions do not incorporate all the parameters of importance to estimate emissions (i.e., the equations are essentially incorrect). For example, the standard method used to estimate nitrous oxide emissions from fertilizer applications assumes that emissions are directly proportional to the amount of fertilizer applied to the land. It would follow, then, that one could estimate reductions in nitrous oxide by measuring the reduction in the amount of fertilizer applied to the soil. However, studies have shown that significant reductions in nitrous oxide emissions can be accomplished by simply changing the *timing* of the fertilizer application, producing more pronounced results than those that would expected by just looking at the reduction in the amount of fertilizer applied to the soil. In this case, the standard method would significantly underestimate emission reductions.

Work on this area of research would start by: (1) studying the level of uncertainties associated with the different emissions sources, (2) identifying potential new sources not being considered in existing inventories, and (3) prioritizing which methods to study in detail with field studies and/or model development work. An example of a potential new source of emissions not being considered in the existing inventory is composting. The current assumption is that composting is an aerobic process that does not result in nitrous oxide and methane emissions. In practice, however, composting may generate substantial amounts of GHG emissions, because anaerobic pockets inside the composting pile create ideal conditions for methane and nitrous oxide generation. This distinction is important because composting is an important state strategy being used to reduce the volume of the waste prior to its burial in landfills.

Benefits: Standardized methods to estimate non-CO_2 emissions could be developed, based on more comprehensive, California-focused data. Accurate estimates are necessary for the development of sound emission reduction options.

3.5.3. Development of Supply Curves for California

Research in this area will be heavily coordinated with the inventory methods development work described above. In addition, a number of methodological and macroeconomic integration issues will be studied and implemented.

The roadmap on supply curves commissioned by PIEREA (Rufo 2002) identified a number of ongoing and planned studies developing supply curves for California for the electricity sector. These supply curves mostly consider existing technology and have a time horizon of about 20 years. PIEREA will take these studies and advance the science/art of supply curves by developing methods to extrapolate these relatively short-term supply curves to much longer time horizons that take into account potential technology changes. This project will also advance the science/art by developing curves that identify the adoption barriers of the different options included in the supply curves and their effect on the actual performance of the different options. This process will include the consideration of non-energy costs and benefits that are traditionally not quantified in the development of these curves. It is often difficult enough within the scope of many studies to quantify direct costs and benefits of measures, much less indirect ones. Nonetheless, identification and quantification of indirect costs and benefits is critical to improved modeling of adoption and would increase the credibility of many studies.

The PIER program will also develop the information needed to include the options identified in the supply curves studies in macroeconomic analyses. The addition of this information will allow for the simultaneous consideration of multiple factors that cannot be considered in the preparation of supply curves. For example, changes in energy prices will change the attractiveness of the different options included in the supply curves, but they can only be considered in a dynamic fashion through the use of computable general equilibrium models, or at least partial equilibrium models. These models simulate the entire economy or the part of the economy that is affected by the action considered, and therefore can capture the interaction of the different options or measures with the rest of the economy.

Benefits: This work would develop dynamic supply curves that researchers can use to estimate the long-term costs and benefits of GHG-mitigation measures, over a larger portion of the economy, to make direct comparisons between competing options.

3.6 The Economics of Climate Change Mitigation and Adaptation in California

The previous sections have described how PIER research will improve our knowledge of regional climate change, potential climate impacts on California's ecosystems and water resources, and the possibilities for biological and terrestrial carbon sequestration in California. Integrating and applying the results of this work to policy-making is a primary goal of PIER-sponsored economic research. Economic methods are the primary tools for evaluating the socioeconomic implications of climate change and the costs and benefits of policy responses. Economics is also the primary disciplinary source of theoretical and computational tools for integrating climate science and policy.

Several decades of research on the economics of climate change at the national and international levels—as well as recent PIER-supported work specific to California—provide a foundation for new PIER-sponsored research on the economics of climate change in California. This section summarizes the specific topic areas, and reflects the need for PIER research to address two broad categories of questions:

1. How can the state's policy-makers better understand the complex and uncertain nature of potential climate change impacts on the state's economy, how should we address the economic risks they entail, and how should policy actions be coordinated across different sectors of the economy and different regulatory areas?
2. How can California design and implement cost-effective policies for GHG abatement, how will these policies affect that state's energy system, and how can we ensure that reducing GHGs in California does not impede the state's continued economic growth and vitality?

More precisely, PIER research will address the following questions:

Questions That PIER-funded Activities Should Try to Address

- How will the impacts of climate change and measures to abate GHGs affect the California economy in the coming decades?
- What are the key economic risks for California from climate change, and what are the particular risks from abrupt and / or extreme climate change?
- How will climate change affect the state's integrated water / agricultural system, and what will be the costs and benefits of policies to address potential impacts on this system?
- What are the costs and benefits of both price and non-price-based policies designed to increase energy efficiency in the California economy?
- How will energy-saving technological change affect the costs of carbon-abatement policies in California?
- How should California design regional markets for emissions trading?
- How should GHG-abatement and air quality policies be integrated?
- What are the costs of abating non-CO_2 GHGs?

<u>PIER Short-term Research Projects</u>

PIER's roadmapping process has identified a series of priority topics that would build upon and extend both previous economic research and PIER's current economic research (which is summarized in this section). It must be emphasized that these topics do not constitute an exhaustive list of needed research on the economics of climate change in California. Instead, they have been singled out because they have a strong potential for providing innovative advances that will be particularly relevant to the state's climate policy planning.

The specific research topics reflect three broad themes:

1. **Risk and Uncertainty.** There is a need to view climate change in California as a problem in the economics of risk and uncertainty, directly confronting the fact that we cannot precisely predict climate change, the future evolution of the state's economy, or the exact details of climate / economy interactions.
2. **Economics of Energy.** There is a need to improve our knowledge of the economics of energy, particularly in regard to the costs and benefits of policies that increase energy efficiency.
3. **Integrated Policy Making.** There is a need to carefully integrate climate-related policies with other economic and environmental policies, particularly those involving fiscal and air quality issues.

3.6.1 Integrated Modeling and Impact Analysis

The dominant tools in economics-based climate policy analysis are numerical models of an entire (usually national or world) economy. These computable general equilibrium (CGE) models represent the detailed interactions of supply and demand and the decisions of households and firms, typically over long time scales. In energy and climate applications, they are used to estimate the costs of price-based policies (carbon or energy taxes, or tradable emissions permit systems) to reduce GHG emissions, as well as the costs of climate change impacts.

A first step in PIER research will be to adapt an existing CGE model of California to estimate the potential impacts of climate change and GHG mitigation policies on the overall state economy. This effort will provide a benchmark for further work and a first assessment of the possible aggregate economic impacts of climate change and GHG policy on California. This modeling will be based, in part, on the new California energy balances described in Section 3.5, which will ensure that energy demand flows in the state are modeled accurately. In addition, the state CGE modeling effort will provide an initial integrating framework that will incorporate results of the PIER research on water and agriculture, energy demand, technological change, and other key areas. For example, this CGE modeling will be able to apply the results of the PIER research on costs of forest and soil carbon sequestration from Section 3.4 to the study of the costs and benefits of carbon abatement policies in California. The CGE work will also analyze the potential for California to implement "revenue recycling"—that is, to use proceeds from measures such as auctioned tradable GHG emissions permits to reduce taxes on consumption or capital investment, or otherwise improve the state's fiscal balances.

The PIER plan for computational modeling reflects a well-known limitation of the standard CGE approach. This type of model is typically deterministic, which means that it assumes that all future events—whether purely economic or involving climate change impacts—are perfectly known. Although such an evaluation can provide a useful first approximation in many instances, this assumption is clearly problematic for application to climate policy, for a variety of reasons. First, on the time scales involved (decades or more) perfect foresight becomes implausible, even in the absence of climate change. Second, exact prediction of regional climate change is beyond scientific capability and likely to remain so; instead, regional climate science can provide as an input ranges of possibilities of how global climate change may impact California. Third, it is well-established that estimating the economic costs of GHG abatement depends on assumptions regarding future technological progress, particularly relating to energy efficiency, which is in turn is difficult or impossible to predict.

For these reasons, PIER will support the development of a new modeling framework to analyze the economics of climate change in California that will take account of risk and uncertainty. The appropriate design of this framework will be the first focus of research, for this effort will take place at the current frontiers of modeling. A primary aim of this work will be to determine how to achieve a reasonable level of model detail while maintaining computational tractability. From a policy perspective, the goal of this work will be to enable policy-makers to determine robust strategies in response to uncertain climate, economic, and technological change: these are dynamic policies that have a high—but not certain—likelihood of success across a wide range of possible futures.

This decision-analysis framework will be particularly important for applying the results of PIER work on regional climate change to policy analysis and implementation. This work will provide a large range of plausible scenarios for the future evolution of the regional climate, rather than one or a small number of "best guesses." A risk-and-uncertainty-based integrated modeling approach is essential for policy-makers to analyze the economic implications of different scenarios and to identify the most effective ways to manage the risks they entail.

Both the CGE modeling and new decision-analysis framework will be used to integrate and apply findings from new PIER research on the sector-specific impacts of climate change in California. Previous work on climate impacts has documented the potential vulnerabilities of both natural and economic systems on international, national, and regional levels extensively. Current PIER-funded work on California-specific impacts is assessing potential impacts and costs associated with specific sectors and systems, as well as identifying possible adaptation or mitigation measures to address these impacts; the focus of this work includes agriculture, water, ecosystems, and timber. To extend this research, PIER will focus on better understanding key risks and uncertainties, and develop models that will enable policy-makers to address them effectively, emphasizing the following topics.

First, almost all work to date on climate impacts—including PIER's current work on California—has been based on the assumption of gradual, smooth climate change. There is increasing recognition and concern among atmospheric scientists, however, that climate change in the coming century may entail abrupt and/or extreme shifts, whether at the global or regional level. From the standpoint of economic analysis, this difference is critical: low-cost adaptation is likely to be difficult or impossible in the case of abrupt or extreme changes; therefore, the economic impacts will be larger. Accordingly, PIER will emphasize this type of potential climate change in its economic research.

Second, standard economic models typically assume optimal behavior on the part of households and firms, and do not represent institutional factors such as policy or regulatory constraints on economic decisions. Like the "perfect foresight" assumption discussed in the previous section, these assumptions provide a useful benchmark in many applications, and dramatically simplify certain technical aspects of modeling. However, they are problematic in analyzing critical economic aspects of climate change. California sectors and systems that may be most vulnerable to climate change—such as the integrated water, energy, and agricultural system—operate under substantial institutional constraints. These existing "real-world" factors will play a major role in the state's formulation of policies to address climate change. Similarly, the decision rules actually used by economic agents may deviate considerably from the ideal posited in the standard economic treatment.

PIER will focus research that addresses these issues (i.e., non-smooth climate change, institutional factors, and realistic decision rules) on California's water and water-related sectors. In California and neighboring states, a major pathway by which increased climate variability and change will affect the region's society and economy is through the impact on streamflow within the region and on the region's developed water supply. Any change in the developed water supply will have important consequences for the allocation of water between agricultural water users, urban water users, hydropower generation, and in-stream uses of water for water-based recreation and ecosystem services. Each of these stakeholder groups may face increased costs and/or reduced benefits as the result of a reduction in the reliability of water availability.

The goal of this research is to assess the impacts on each sector from a change in water supply reliability. Researchers will develop a set of quantitative and explicitly probabilistic measures of water supply reliability for the various agricultural and urban users of water at different locations around the state, using existing climate conditions, and based on the actual experience of the operation of the California water system over the past 20–30 years (since the early days of the State Water Project). Researchers will then use these measures to develop sets of marginal benefit functions, showing the incremental benefit or losses associated with changes in the reliability of water supply for agricultural users, urban users, and hydropower generation at various California locations. This analysis will utilize the empirical measures of supply reliability under existing conditions for agricultural and urban users in different parts of the state, which will be derived from the hydrologic analysis described above. A third research component will develop projections and analyses of water use and electricity demand, taking account of location and housing density. PIER research will estimate both the monetary and non-monetary magnitudes of these impacts, incorporating several methodological innovations that will reflect the research priorities described above: explicit treatment of the surface water supply system, inclusion of regulatory and legal constraints on the existing process for water allocation, and representation of the actual decision rules employed in California's water system.

Benefits: This effort would provide a benchmark for further work and a first assessment of the possible aggregate economic impacts of climate change and GHG policy on California. The state CGE modeling effort would provide an initial integrating framework that would incorporate results of the PIEREA research on water and agriculture, energy demand, technological change, and other key areas. In addition, this research would provide improved theoretical and empirical tools for understanding the potential impacts of climate change on California's integrated water/energy/economic system, as well as the costs and benefits of potential adaptation and mitigation measures associated with this system. Ultimately, this work would enable policy-makers to develop robust strategies in response to uncertain climate, economic, and technological change.

3.6.2 Energy Efficiency and Technological Change

California's energy system will be a major focus of carbon mitigation policies, whether undertaken directly by the state or implemented as part of broader national or international efforts. Thus, estimating the costs of carbon abatement from a number of policies directed at altering energy demand patterns—including tradable carbon emissions permits, vehicle emissions limits, and end-use energy-efficiency standards—will be a central challenge for California's policy-makers. Although the potential magnitude of these costs has been the central focus of the economic aspects of climate change, that discussion remains extremely contentious.

PIER will therefore sponsor research to improve policy-relevant methodologies and help researchers better understand how economic decision-making and the character of existing markets determine the costs of increasing energy efficiency and/or abating carbon emissions. These advances will in turn provide California's policy-makers with improved tools for implementing carbon mitigation policies. This research will be integrated with that on supply curves (described in Section 3.5.3), to improve the theoretical and empirical basis for the supply curve methodology.

The first area of research focuses on the degree to which energy-efficient technology is optimally allocated by markets in the absence of policy intervention. The focus of this debate has been the so-called "energy efficiency gap": the putative under-adoption of such technology without government policies to encourage (or compel) it. (This is also commonly referred to as the "top-down/bottom-up" debate.) Technologists have consistently argued that the gap is both real and substantial; whereas, economists have strongly questioned this claim on both theoretical and empirical grounds.

The persistence of this controversy has significant policy implications. California has a substantial investment in—and indeed has been a leader in deploying—policies based on the "bottom-up" perspective, such as appliance energy efficiency standards and utility demand-side management. Looking ahead, such policies will almost certainly form a major component of California's carbon mitigation efforts. According to standard economic models, the benefits of these policies cannot exceed their costs. This is a quandary demanding careful attention from economists and technology researchers.

PIER research will aim to understand the sources of this dispute both empirically and theoretically and to develop improved empirically based economic models of energy-efficiency decision-making. The first phase will examine carefully the literature on the "gap," to determine the robustness of findings in this literature to sources and quality of data, the soundness of the theoretical models employed, and the role of assumptions regarding market structure. The second phase will develop new models of consumers' and firms' efficiency-related choices, building on the insights and methods of behavioral economics—a rapidly developing field that integrates theoretical economic methods with the insights of cognitive psychology and other social sciences, and grounds theoretical models firmly on detailed empirical observation.

The second research area is the measurement and modeling of energy-related technological change. It is well-established in energy modeling literature that assumptions regarding technological change have a substantial impact on modeled estimates of the costs of reducing energy demand or carbon emissions. Traditionally, energy-economic simulation models (such as the CGE models discussed in Section 3.6.1) have represented technological change as "autonomous" or "exogenous," that is, influenced neither by the workings of the market system nor by policy actions on the part of government.

In recent years, however, economists have made significant progress in understanding the processes of technological innovation and change in a modern economy, and in developing theoretical and empirical models that represent these processes. A central theme in this research is that technological innovation and invention are *economic* activities that respond to incentives and market forces —that is, that they are endogenous to the economy. A related phenomenon is known as "learning-by-doing," the decline in the cost of producing a technology that results from manufacturing experience.

Both endogenous technological change and learning-by-doing phenomena have recently begun to receive the attention of the modeling community, and preliminary results strongly indicate that including either phenomenon in a CGE or other simulation model has significant effects on modeled estimates of the costs of reducing energy consumption or carbon emissions. They are therefore important potential components of the economic modeling of California's economy and its response to GHG-reduction policies. The PIER program will support research on endogenous technological change and learning-by-doing in order to better understand the significance of these phenomena in California industries, and their implications for climate policy, and to better model the overall state economy in the context of GHG abatement studies. Researchers will first develop case studies on selected state industries to model and measure learning-by-doing and its relation to other key parts of the industrial innovation process, such as the adoption and diffusion of new technology. Second, they will study ways of incorporating both endogenous technological change and learning-by-doing in the program's CGE modeling (see Section 3.6.1) and in the new computational modeling framework that will be developed. The work will focus both on technical issues involving the numerical solutions of models with these elements, and on applied policy studies.

An important area of research related both to the energy-efficiency gap and to technological change is the rapidly increasing role of information technology (IT) in the California economy. There is an emerging consensus that IT may be shifting the American economy to a higher level of aggregate productivity. At the micro level, IT is dramatically changing the nature of many business practices, with potentially significant firm-level productivity effects. The implications of the IT "revolution" for energy trends, however, remain to be explored for the most part. The relationship between IT and energy could have significant implications, both for the design of policies to mitigate GHG emissions and for the response of the larger economy to these policies. This is true not just for the national economy, but also for California in particular, where IT plays a substantial and increasing economic role. Current levels of funding do not allow for a specific PIER research project on IT and energy. Because of the potential importance of this area, however, PIER will actively seek co-funding to study how IT may affect California's energy system and its response to carbon abatement policies. This work would examine the relations among economic growth, IT diffusion, and energy consumption in the overall state economy, as well as the detailed economic characteristics of IT-based energy management and control technologies in households and firms. The results of this work would be incorporated in the CGE and further aggregate modeling sponsored by PIER.

Benefits: This project would help improve understanding of the role of energy efficiency in reducing GHG emissions by quantifying benefits and costs from these measures and exploring the optimal implementation and use of energy efficiency technologies for this purpose.

3.6.3 Non-CO_2 GHGs and Markets for Emissions Trading

Economic modelers have recently called attention to the importance of integrating CO_2 with other GHGs in devising mitigation strategies. Their findings include substantial cost reductions resulting from a multi-gas (as opposed to a CO_2-only) approach to reaching GHG concentration targets, with little difference in climate or ecosystem effects between the two. At the same time, it is known that a number of policies to control CO_2 emissions would also reduce emissions of other pollutants, with important implications for regional air quality. Moreover, these reductions would yield health and other benefits on a much shorter timescale than that applying to climate-change-mitigation effects of CO_2 reductions. As a consequence, the costs of CO_2 mitigation actions are likely to be reduced once analyses account for these “co-benefits” or “ancillary benefits.”

Such results demonstrate the importance of integrating carbon and non-carbon mitigation measures both analytically and in the formulation of California policy. Given the State’s strong commitment to maintaining air quality, as well as the likelihood of broad climate-related mitigation efforts in the coming decades, PIER will support research on developing a multi-GHG approach that fully exploits potential synergies and reaps ancillary benefits. Simultaneously, PIER will fund research to improve the methodology for constructing marginal cost or supply curves for non-CO_2 greenhouse gases. The aim here will be to develop a theoretical model that allows for empirically verifiable negative cost abatement as well as cost-reducing technological change. This work will be integrated with that described in Section 3.5.2.

Emissions trading has emerged in recent years as a favored instrument for reducing GHG emissions, specifically as an alternative to direct government regulation of emissions through “command and control” measures. An emissions trading system imposes a cap on the total emissions of a pollutant while providing incentives for abatement to be undertaken by whichever emitters can do so at the lowest cost, thereby minimizing the aggregate cost of meeting the overall emissions cap. Emissions trading gained considerable currency as a result of its successful implementation in 1990 to reduce SO_2 emissions from electric power generators. Looking ahead, there is a very high likelihood that some form of emissions trading system—national, international, or both—will eventually be put into place to achieve GHG mitigation targets.

In the meantime, however, smaller-scale trading regimes are being studied and in some cases implemented. The PIER program will sponsor a feasibility study for a California intrastate trading market. This study will identify and examine the appropriate geographical and sectoral scope, which GHGs would be included, the required institutional mechanisms, and related elements. It will also address implementation issues in the context of emerging (or by-then established) national and international policies. The goal will be to determine the appropriate elements of a regional trading market, whether implemented as a stand-alone state response to climate change or in response to national or international agreements.

<u>Benefits</u>: Multi-GHG reduction strategies would expand and speed air quality benefits, at a lower overall cost. Development of a regional GHG trading market could also speed GHG-emissions reduction.

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